The Birth of Stars

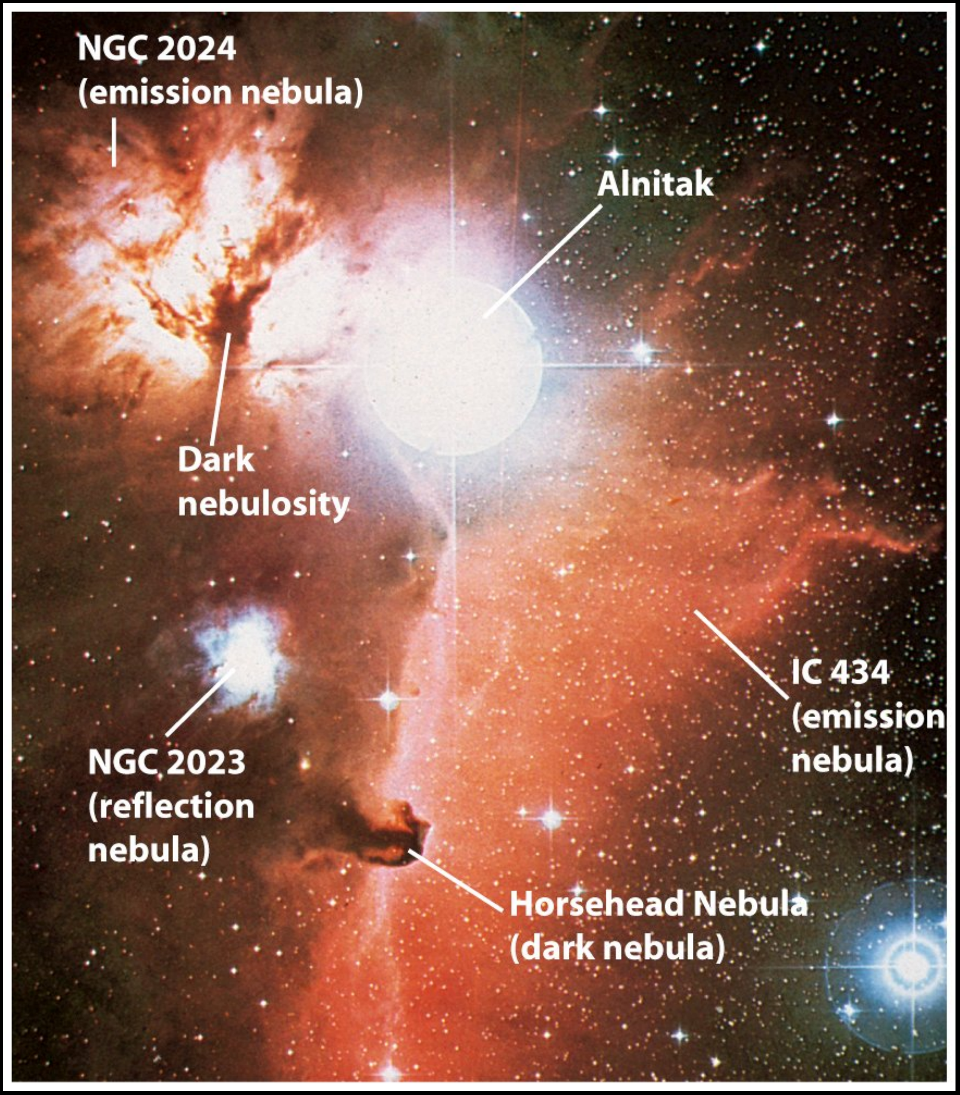
Guiding Questions

1. Why do astronomers think that stars evolve (bad use of term – this is about the birth, life and death of stars and that is NOT evolution)?
2. What kind of matter exists in the spaces between the stars?
3. In what kind of nebulae do new stars form?
4. What steps are involved in forming a star like the Sun?
5. When a star forms, why does it end up with only a fraction of the available matter?
6. What do star clusters tell us about the formation of stars?
7. Where in the Galaxy does star formation take place?
8. How can the death of one star trigger the birth of many other stars?

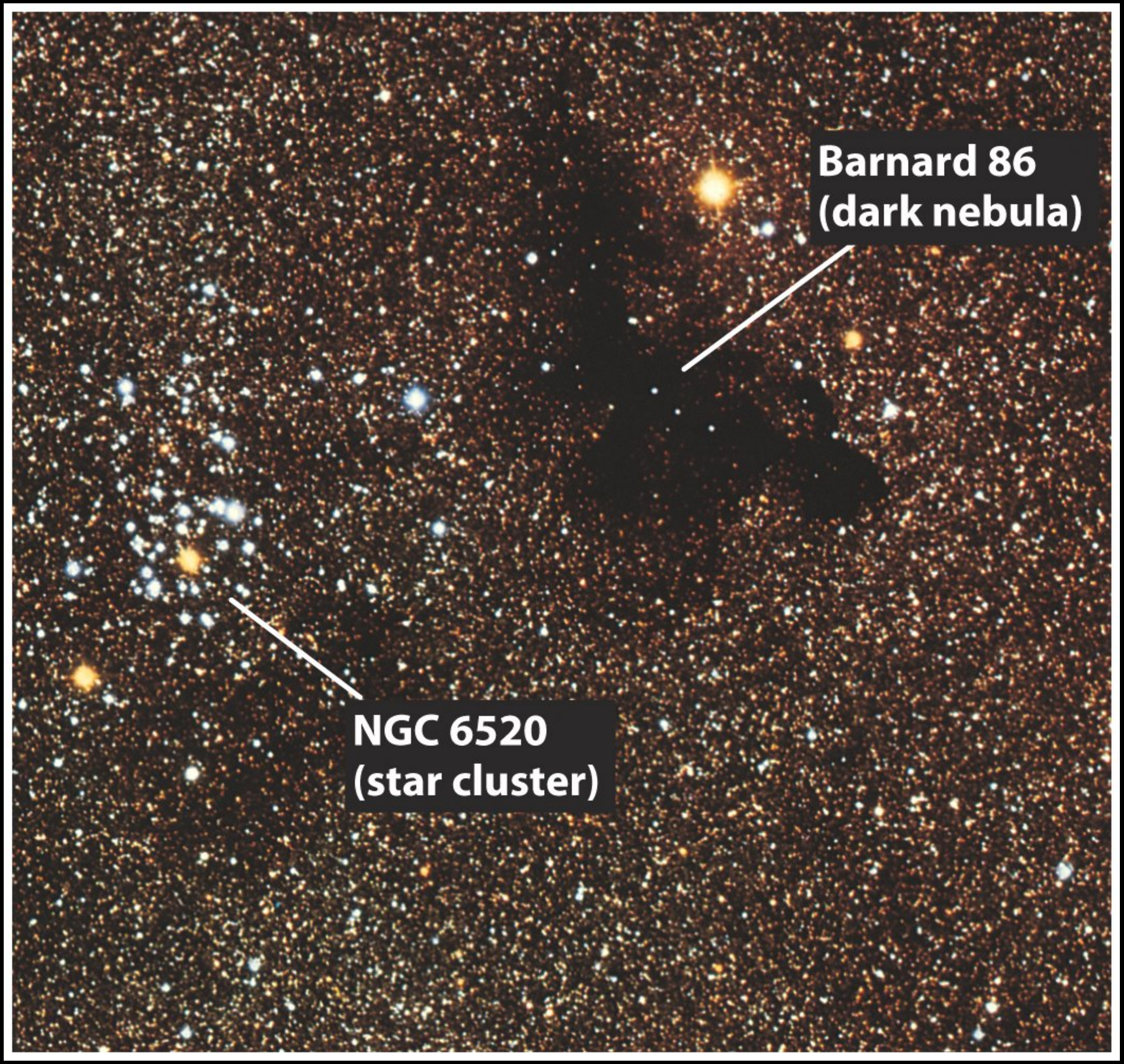
Understanding how stars evolve requires both observations and ideas from physics

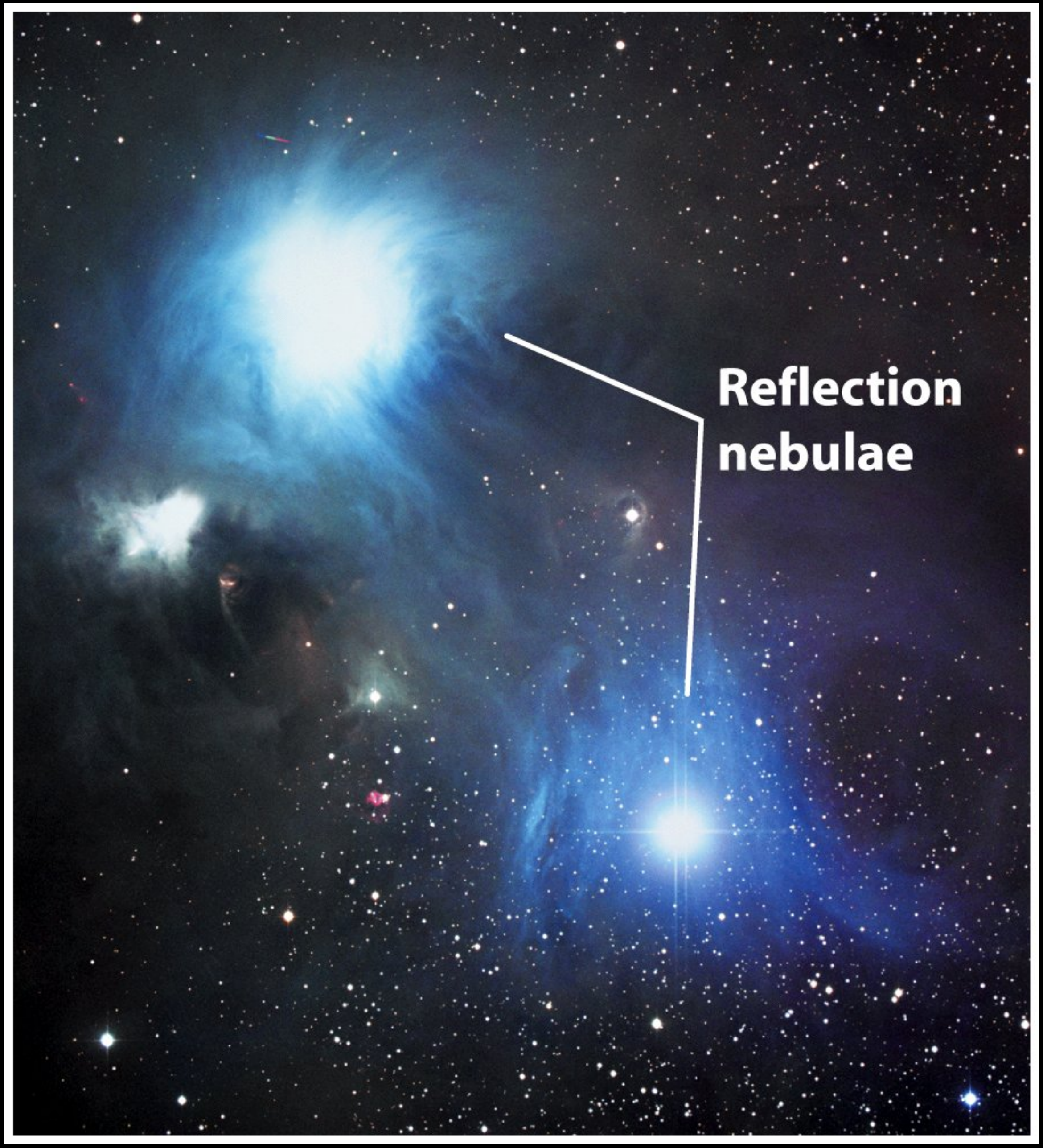
- Because stars shine by thermonuclear reactions, they have a finite life span
  - That is, they fuse lighter elements into heavier elements
    - When the lighter elements are depleted, there is nothing left to fuse
- The theory of stellar evolution (not in the same sense as biological evolution, but more like life cycle development, like growing up) describes how stars form and change during that life span

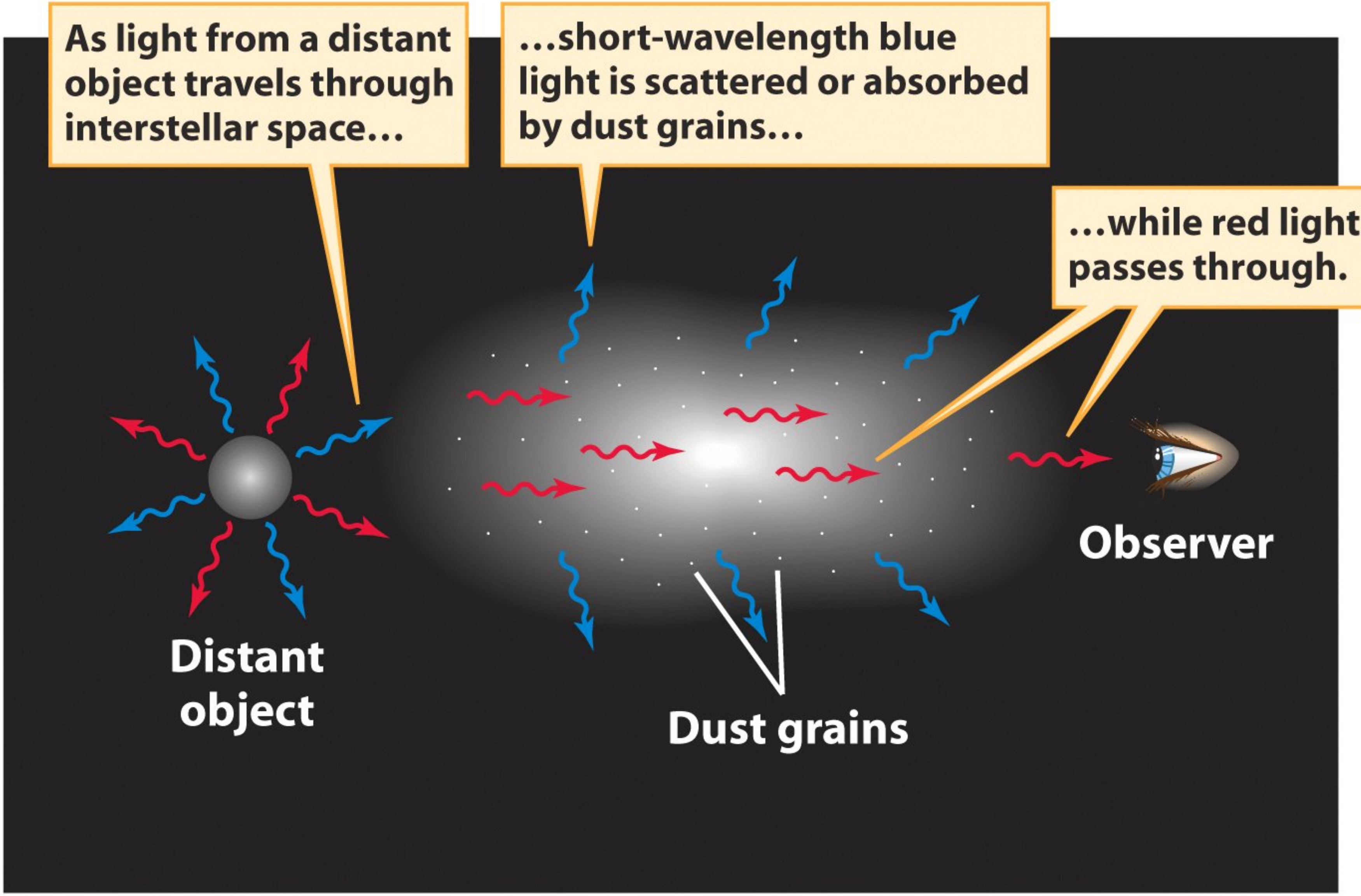
Interstellar gas and dust is ubiquitous the Galaxy



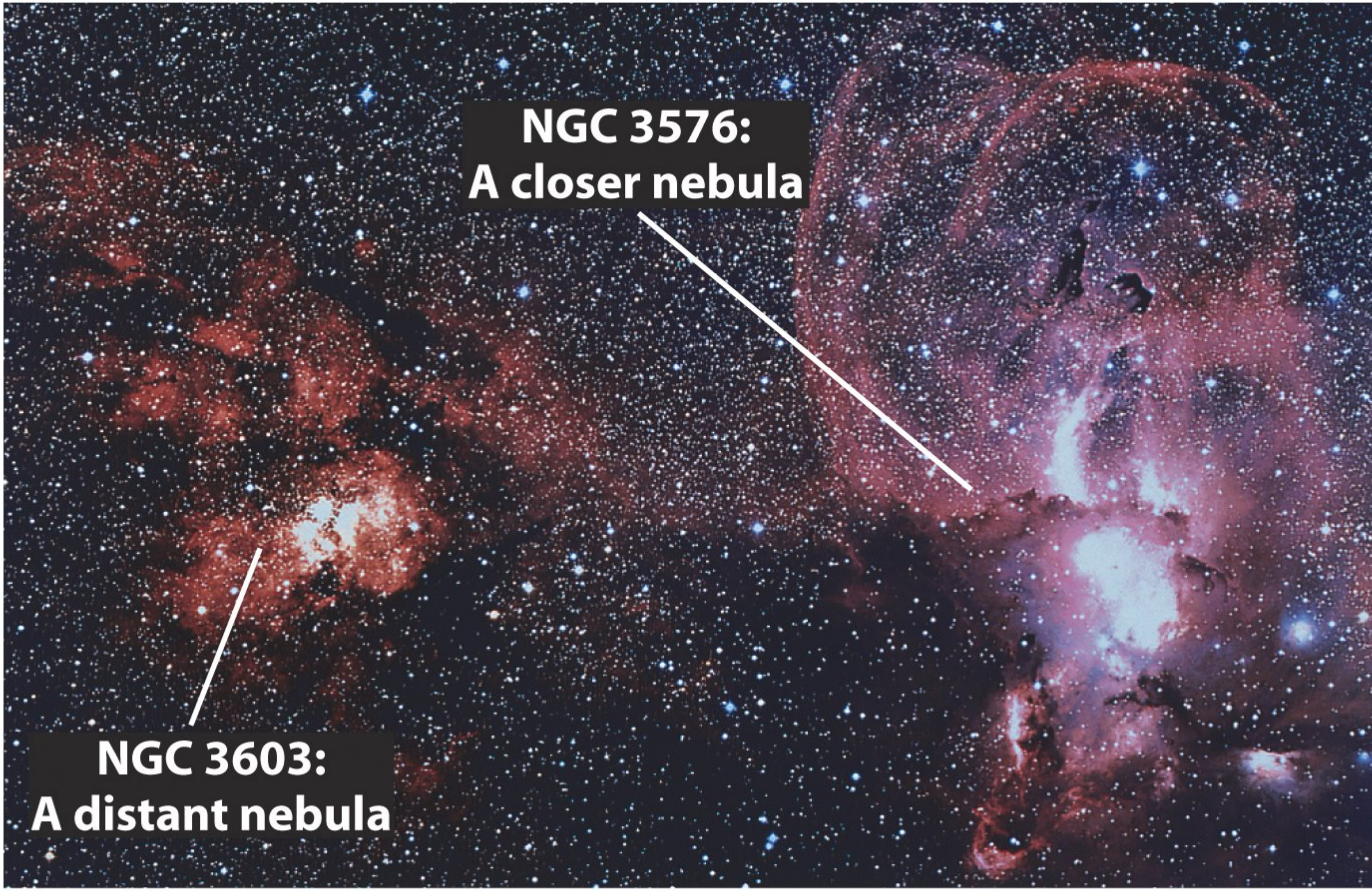
- Interstellar gas and dust, which make up the interstellar medium (ISM), are concentrated in the disk of the Galaxy
- Clouds within the interstellar medium are called nebulae
- Dark nebulae are so dense that they are opaque
  - They appear as dark blots against a background of distant stars
- Emission nebulae, or H II regions, are glowing, ionized clouds of gas
  - Emission nebulae are powered by ultraviolet light that they absorb from nearby hot stars
- Reflection nebulae are produced when starlight is reflected from dust grains in the interstellar medium, producing a characteristic bluish glow


Barnard 86
(dark nebula)
NGC 6520
(star cluster)

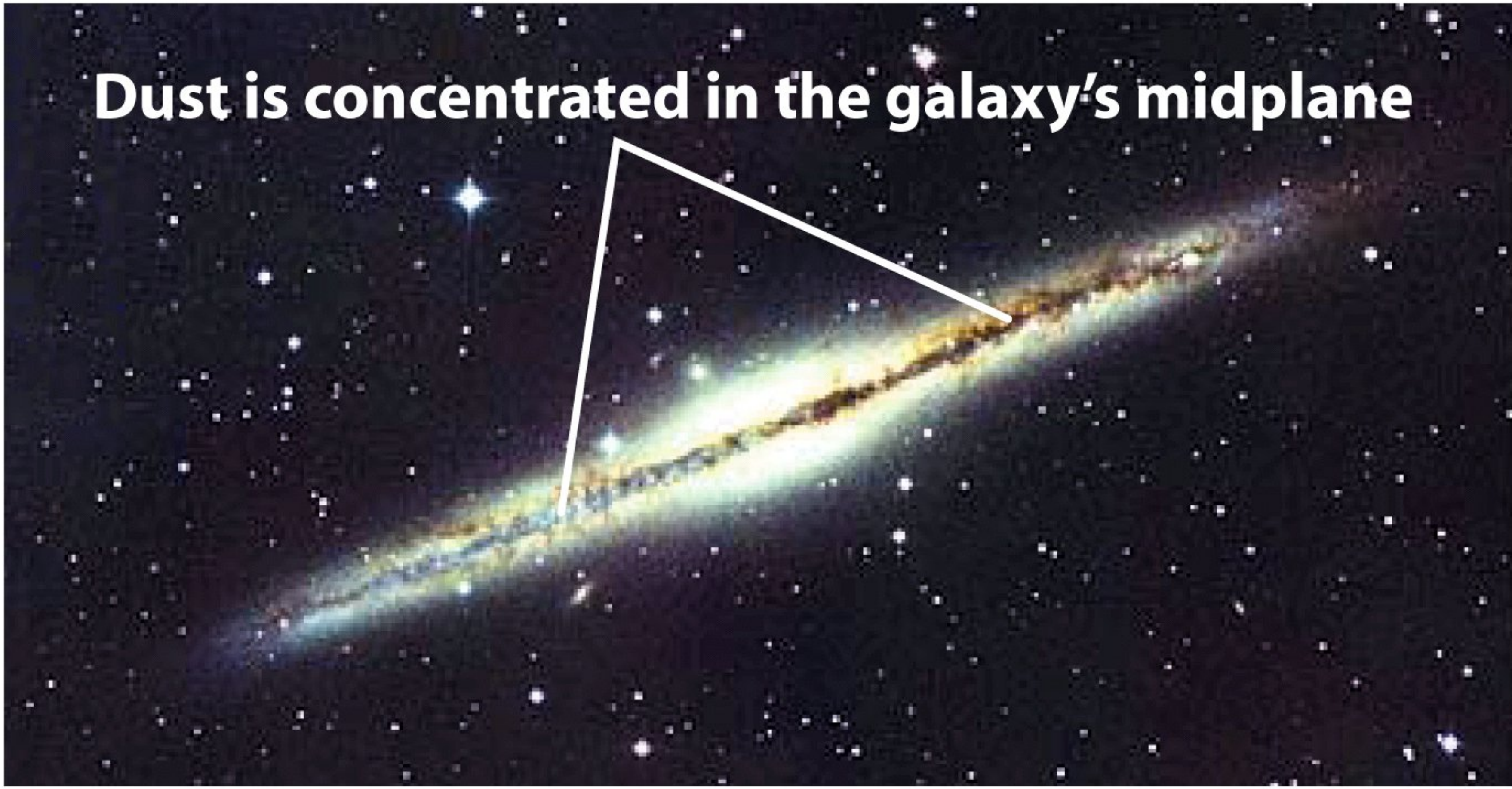

Reflection
nebulae



How dust causes interstellar reddening

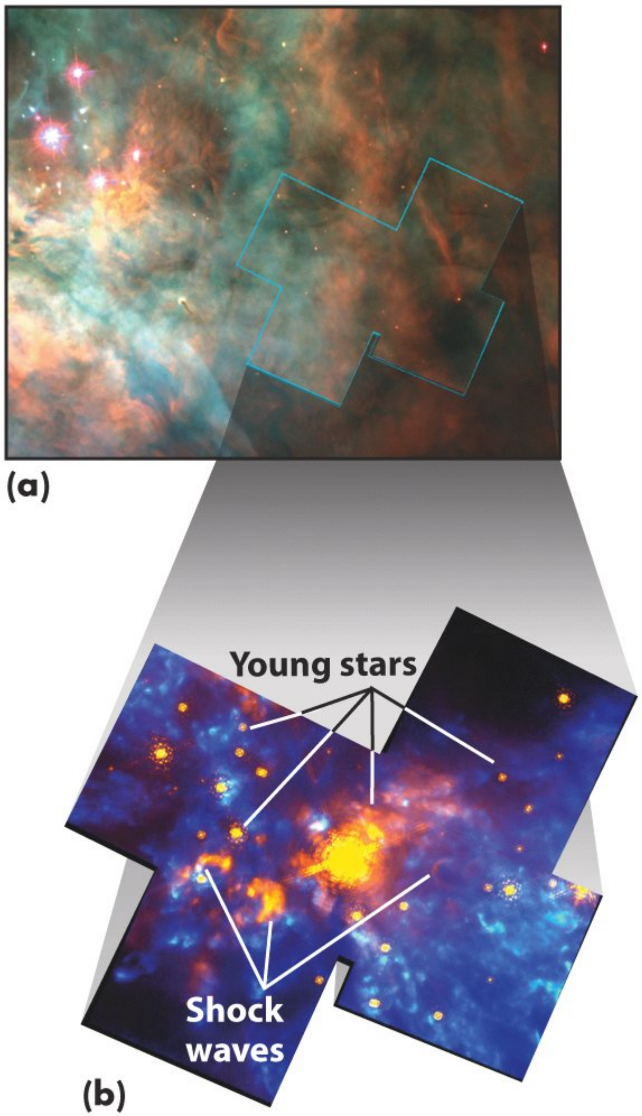


Reddening depends on distance

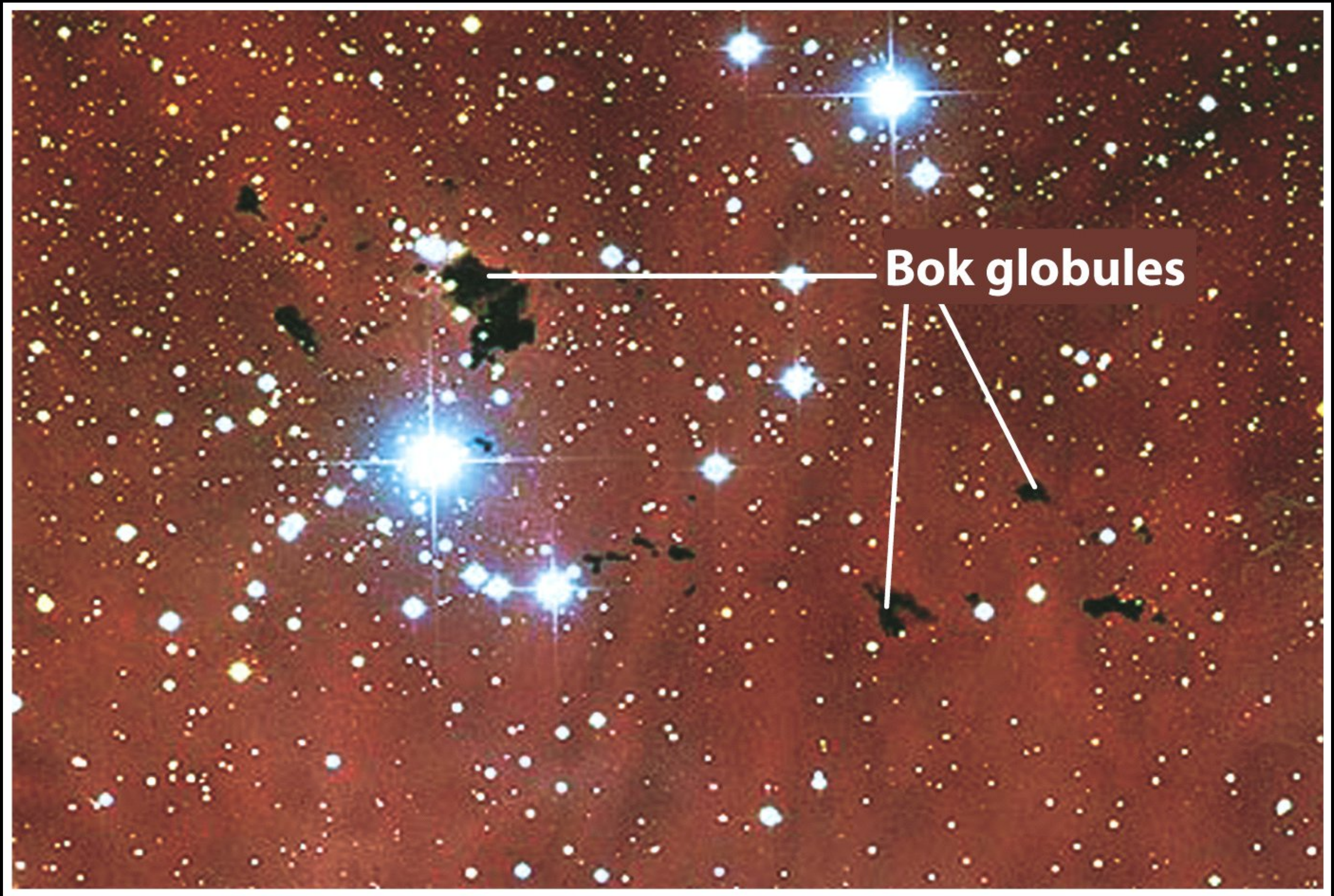


We see spiral galaxy NGC 891 nearly edge-on

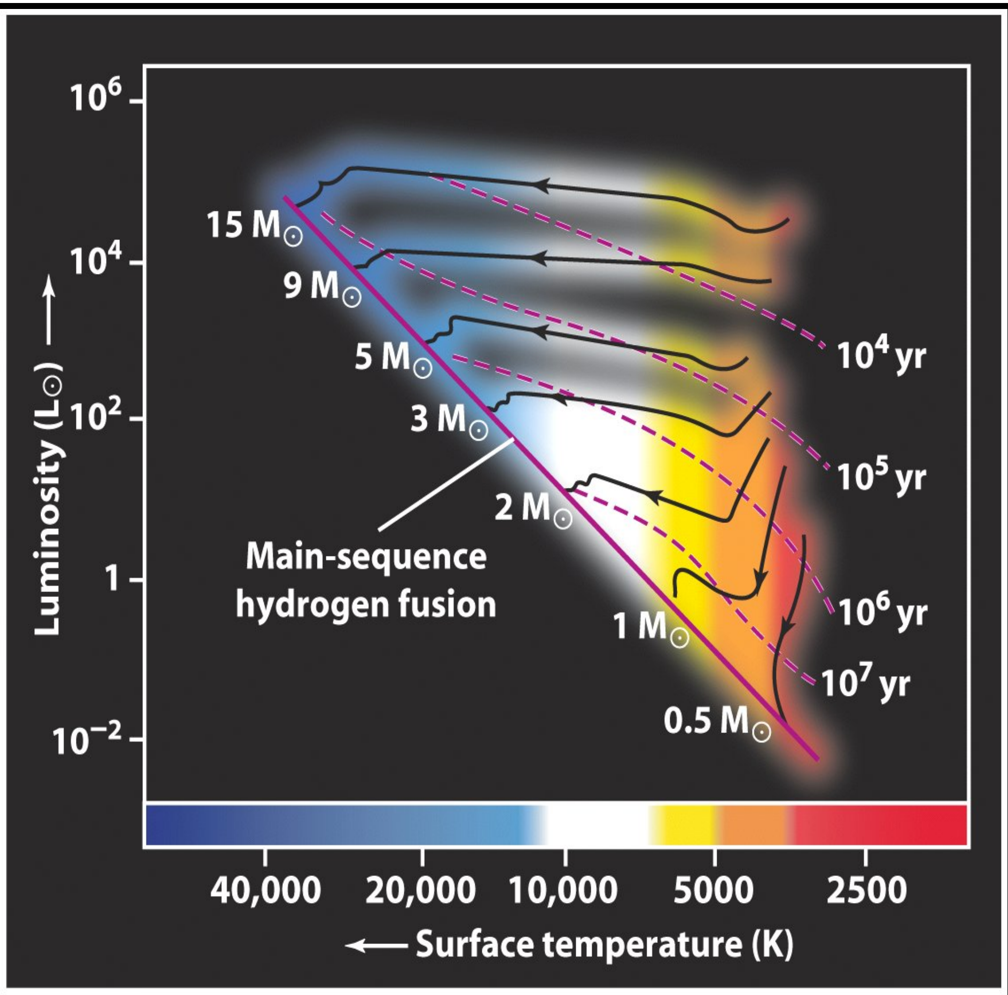
Protostars form in cold, dark nebulae



- Star formation begins in dense, cold nebulae, where gravitational attraction causes a clump of material to condense into a protostar
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing

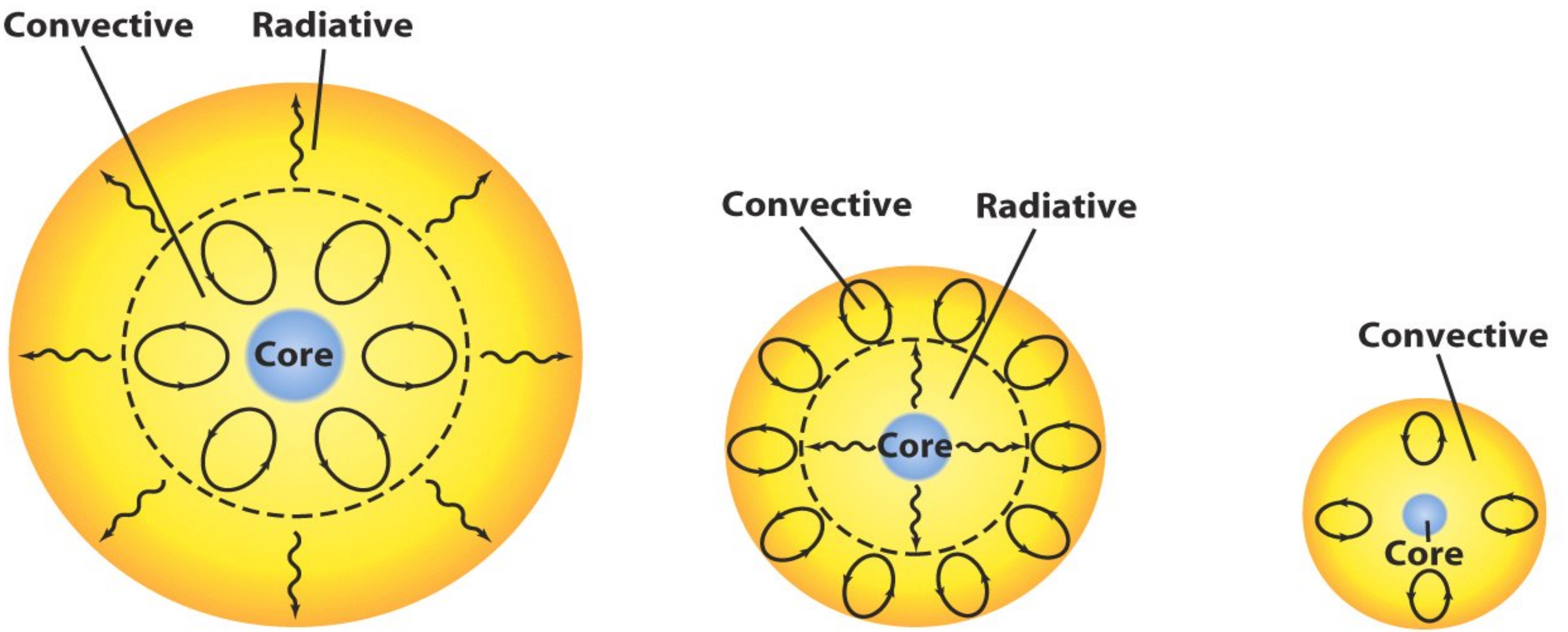

Bok globules

Protostars develop into main-sequence stars



- A protostar's relatively low temperature and high luminosity place it in the upper right region on an H-R diagram
- Further evolution of a protostar causes it to move toward the main sequence on the H-R diagram
- When its core temperatures become high enough to ignite steady hydrogen burning, it becomes a main sequence star

The more massive the protostar, the more rapidly it evolves



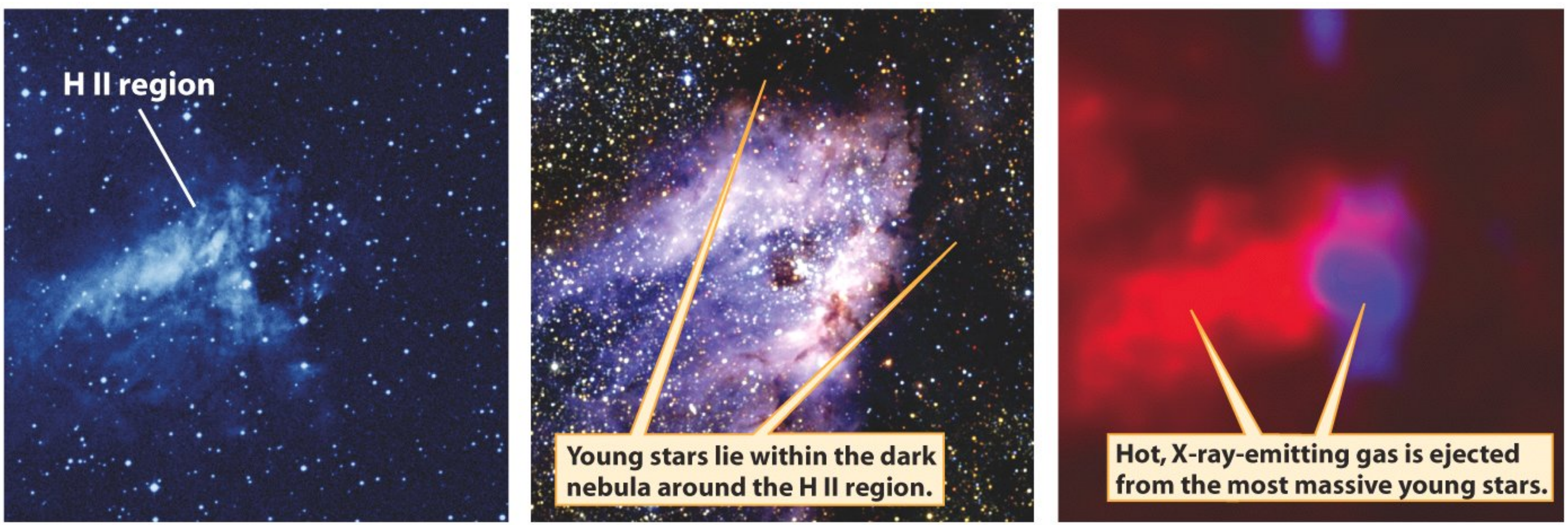
(a) Mass more than about 4 $M_\odot$: Energy flows by convection in the inner regions and by radiation in the outer regions.

(b) Mass between about 4 $M_\odot$ and 0.8 $M_\odot$: Energy flows by radiation in the inner regions and by convection in the outer regions.

(c) Mass less than 0.8 $M_\odot$: Energy flows by convection throughout the star's interior.

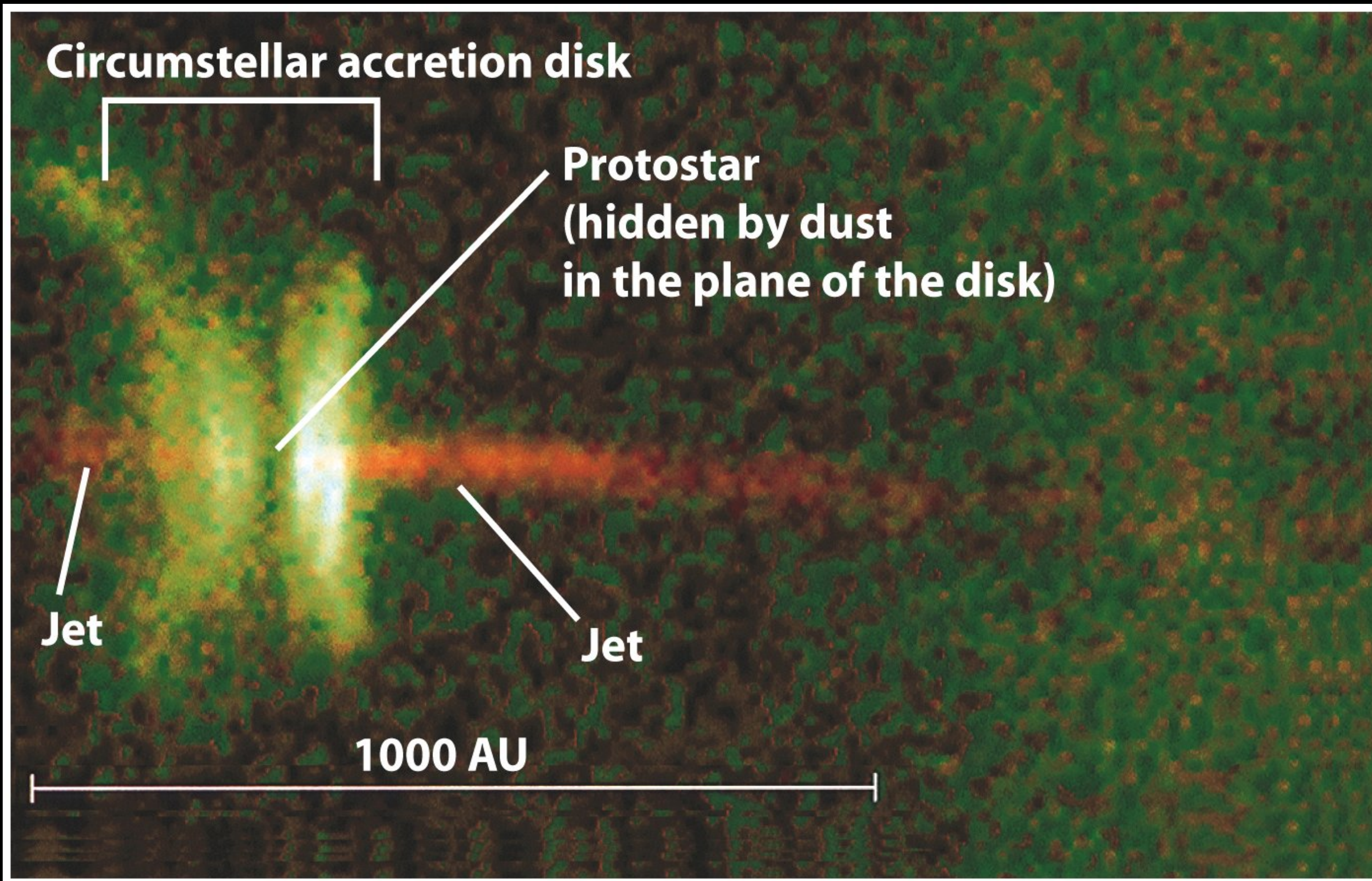
During the birth process, stars both gain and lose mass

- In the final stages of pre-main-sequence contraction, when thermonuclear reactions are about to begin in its core, a protostar may eject large amounts of gas into space
- Low-mass stars that vigorously eject gas are often called T Tauri stars

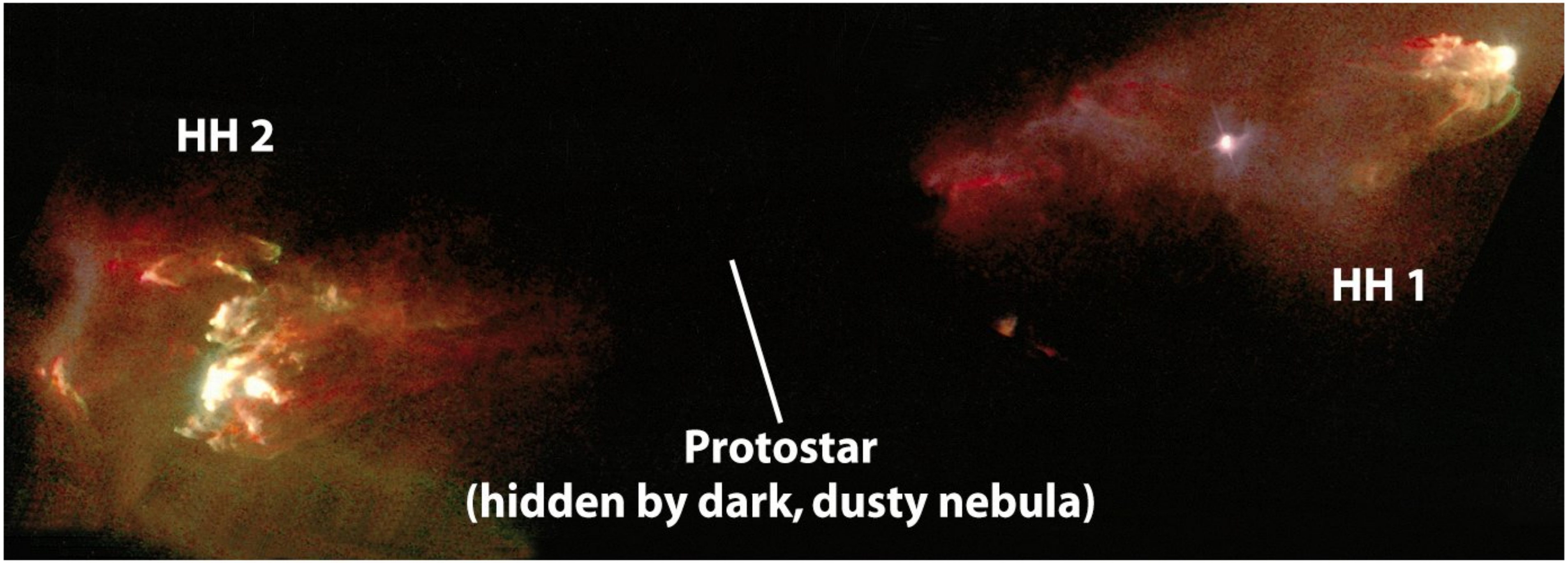


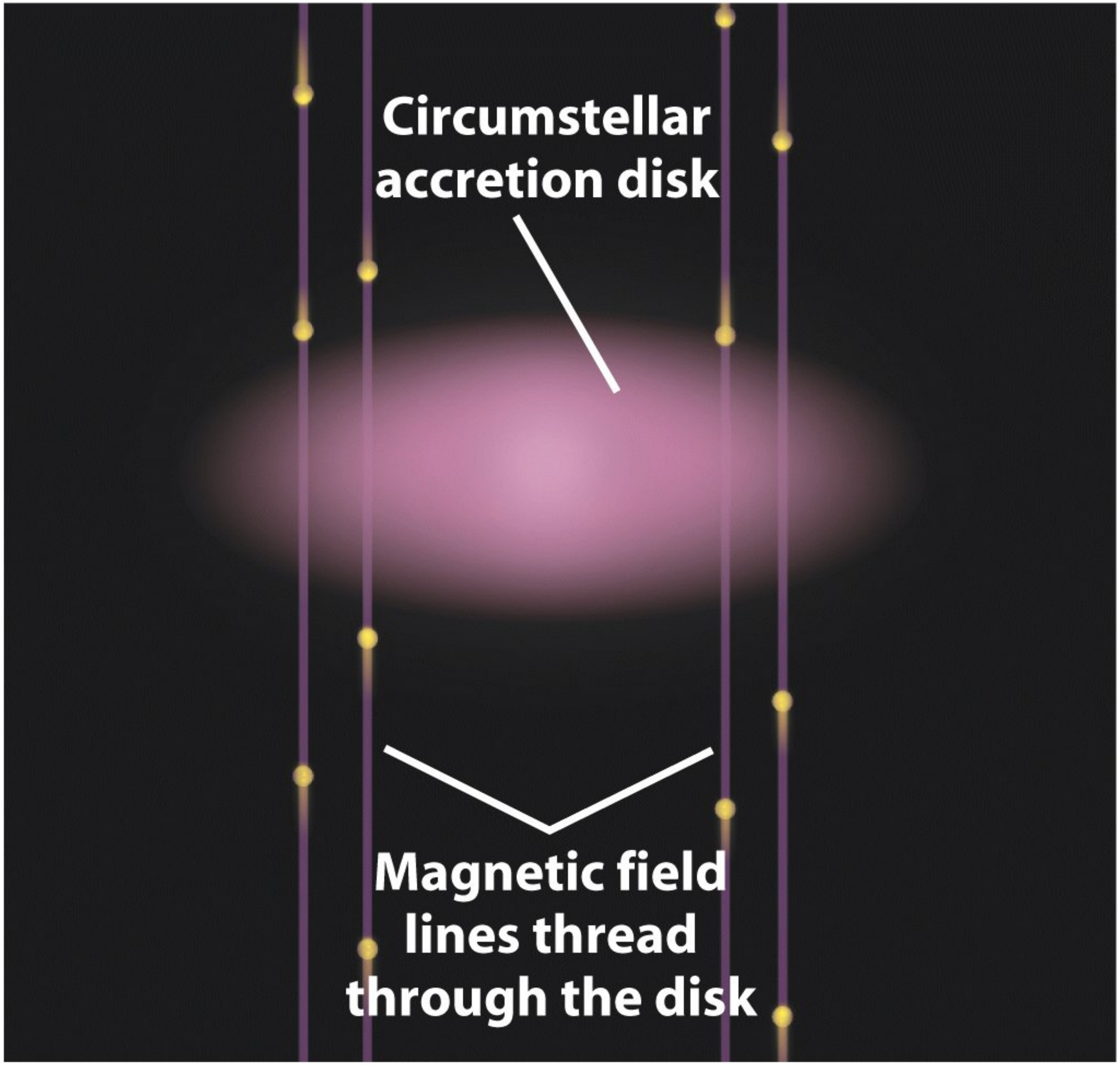
(a) Visible-light image (b) False-color infrared image (c) False-color X-ray image

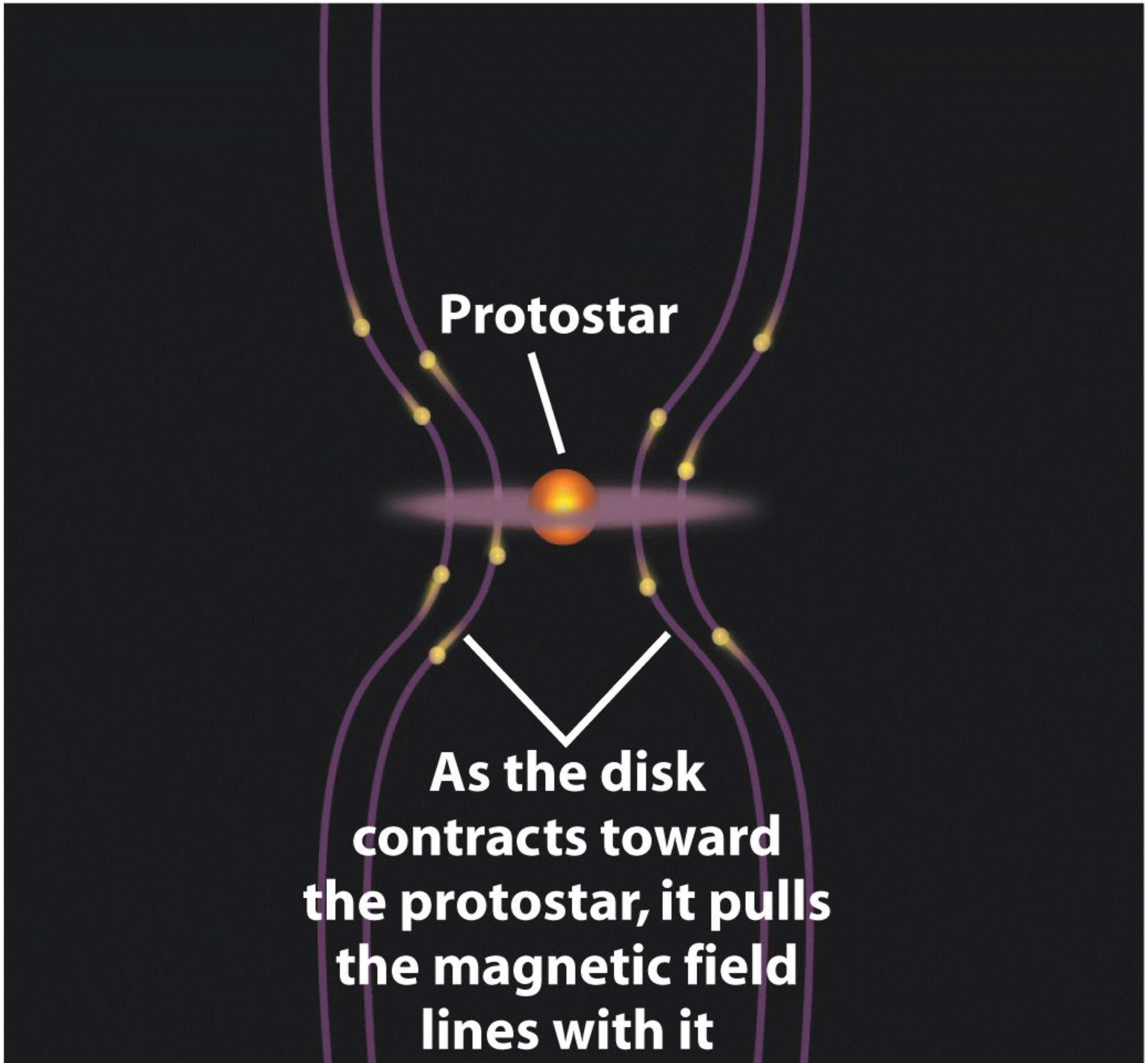
A circumstellar accretion disk provides material that a young star ejects as jets

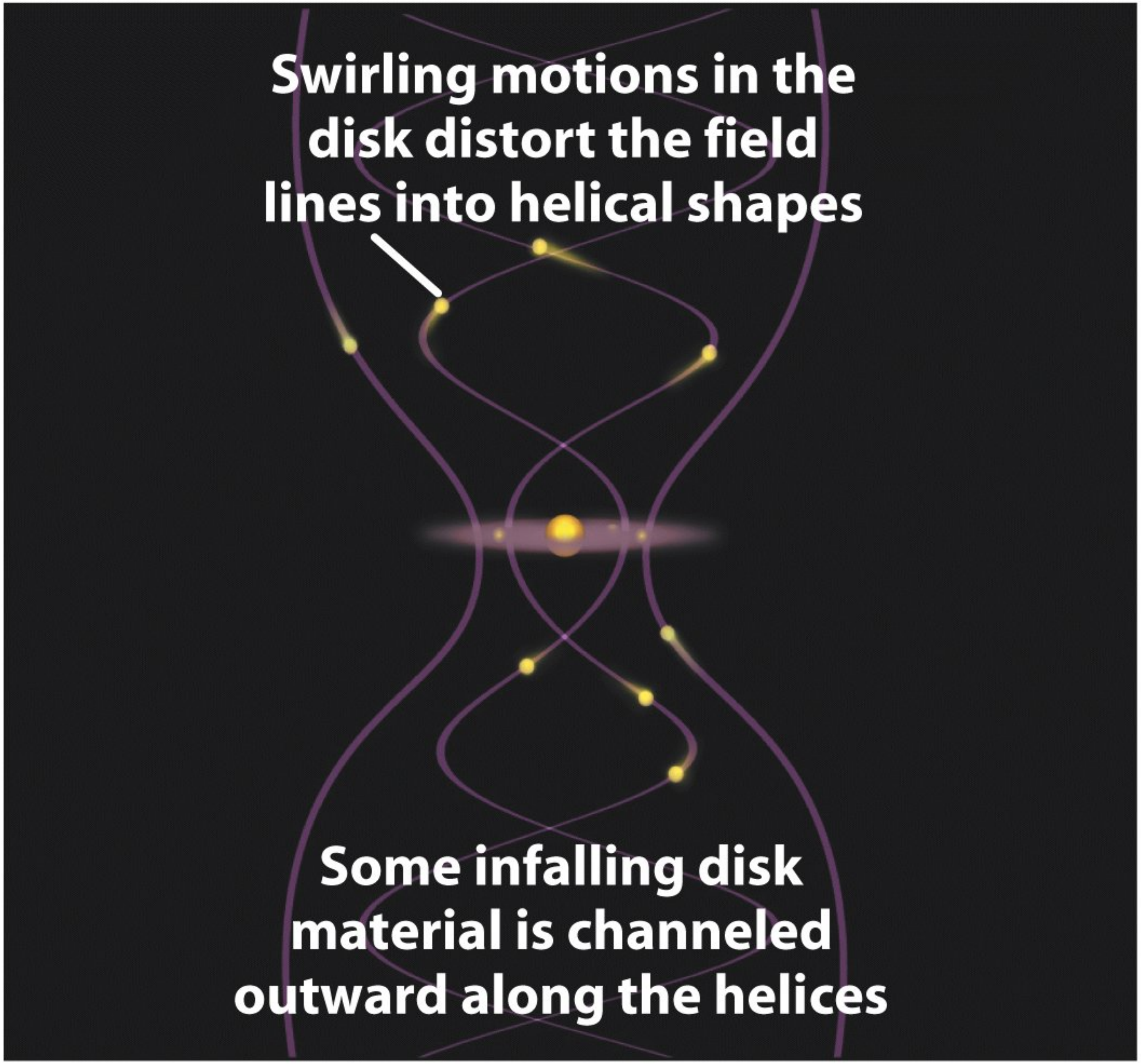


Clumps of glowing gas called Herbig-Haro objects are sometimes found along these jets and at their ends




Circumstellar accretion disk
Magnetic field lines thread through the disk


Protostar
As the disk contracts toward the protostar, it pulls the magnetic field lines with it


Swirling motions in the disk distort the field lines into helical shapes
Some infalling disk material is channeled outward along the helices

Young star clusters give insight into star formation and evolution

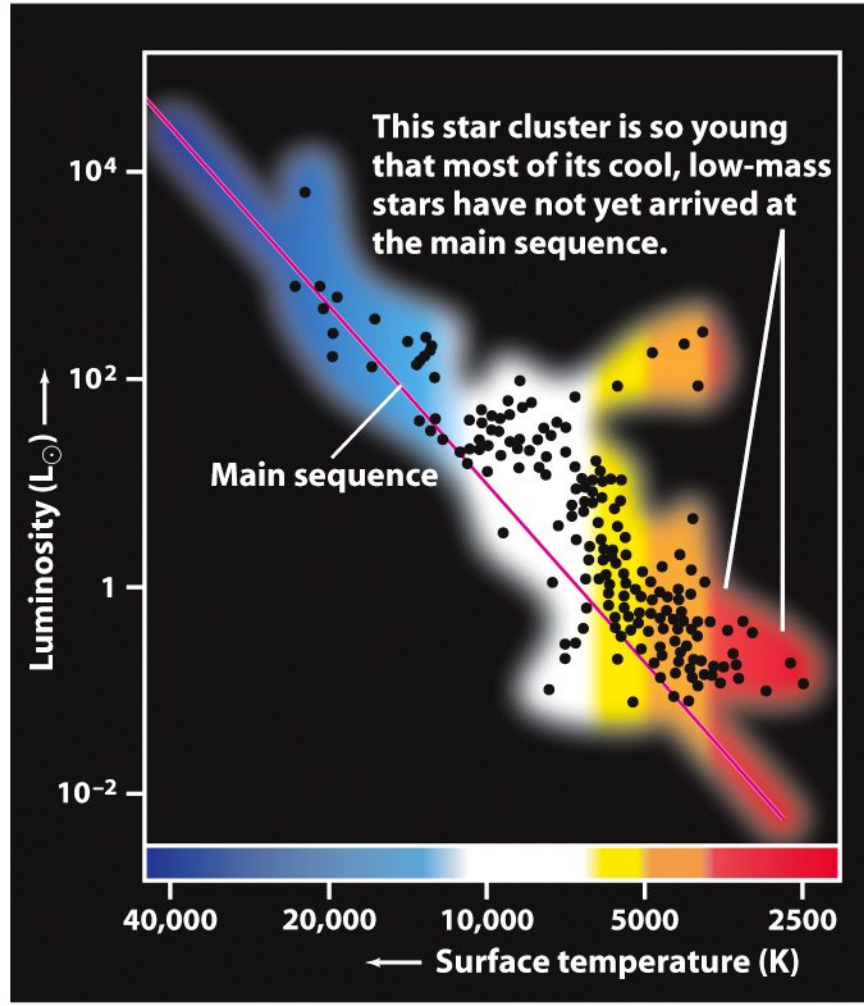
The star cluster NGC 2264

The Pleiades star cluster

- Newborn stars may form an open or galactic cluster
- Stars are held together in such a cluster by gravity
- Occasionally a star moving more rapidly than average will escape, or “evaporate,” from such a cluster
- A stellar association is a group of newborn stars that are moving apart so rapidly that their gravitational attraction for one another cannot pull them into orbit about one another

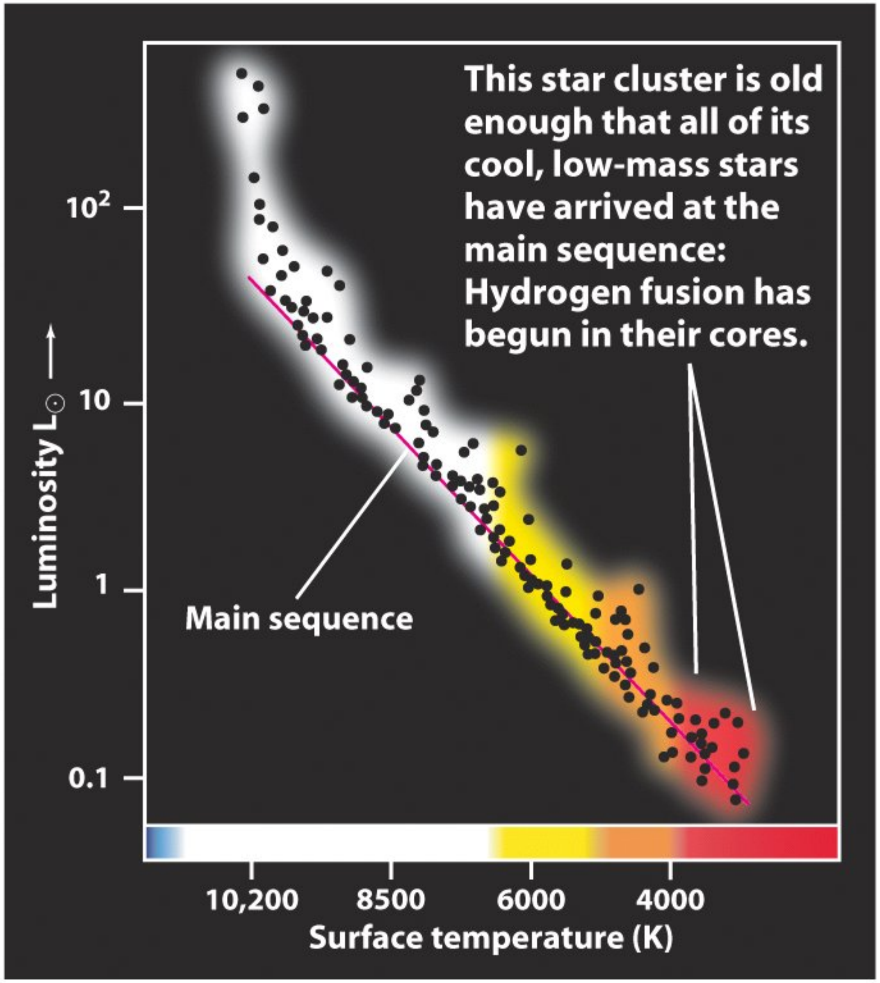

1. This emission nebula (about 2200 pc away and about 20 pc across) surrounds the star cluster M16.
2. Star formation is still taking place within this dark, dusty nebula.
3. Hot, luminous stars (beyond the upper edge of the closeup image) emit ultraviolet radiation: This makes the dark nebula evaporate, leaving these pillars.
4. At the tip of each of these “fingers” is a cocoon nebula containing a young star.
5. Eventually the cocoon nebulae evaporate, revealing the stars.

(a) The star cluster NGC 2264



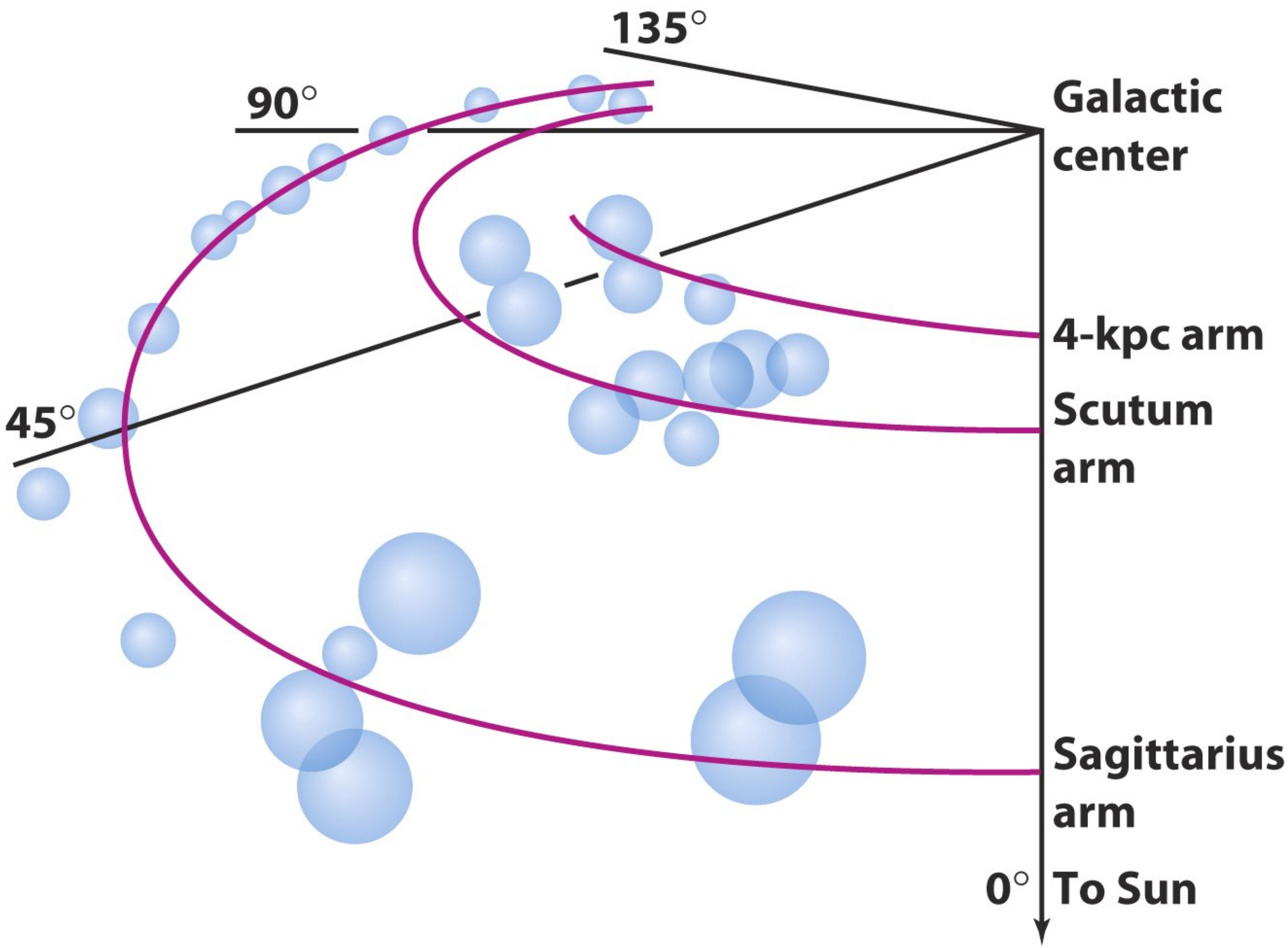
(b) An H-R diagram of the stars in NGC 2264

(a) The Pleiades star cluster

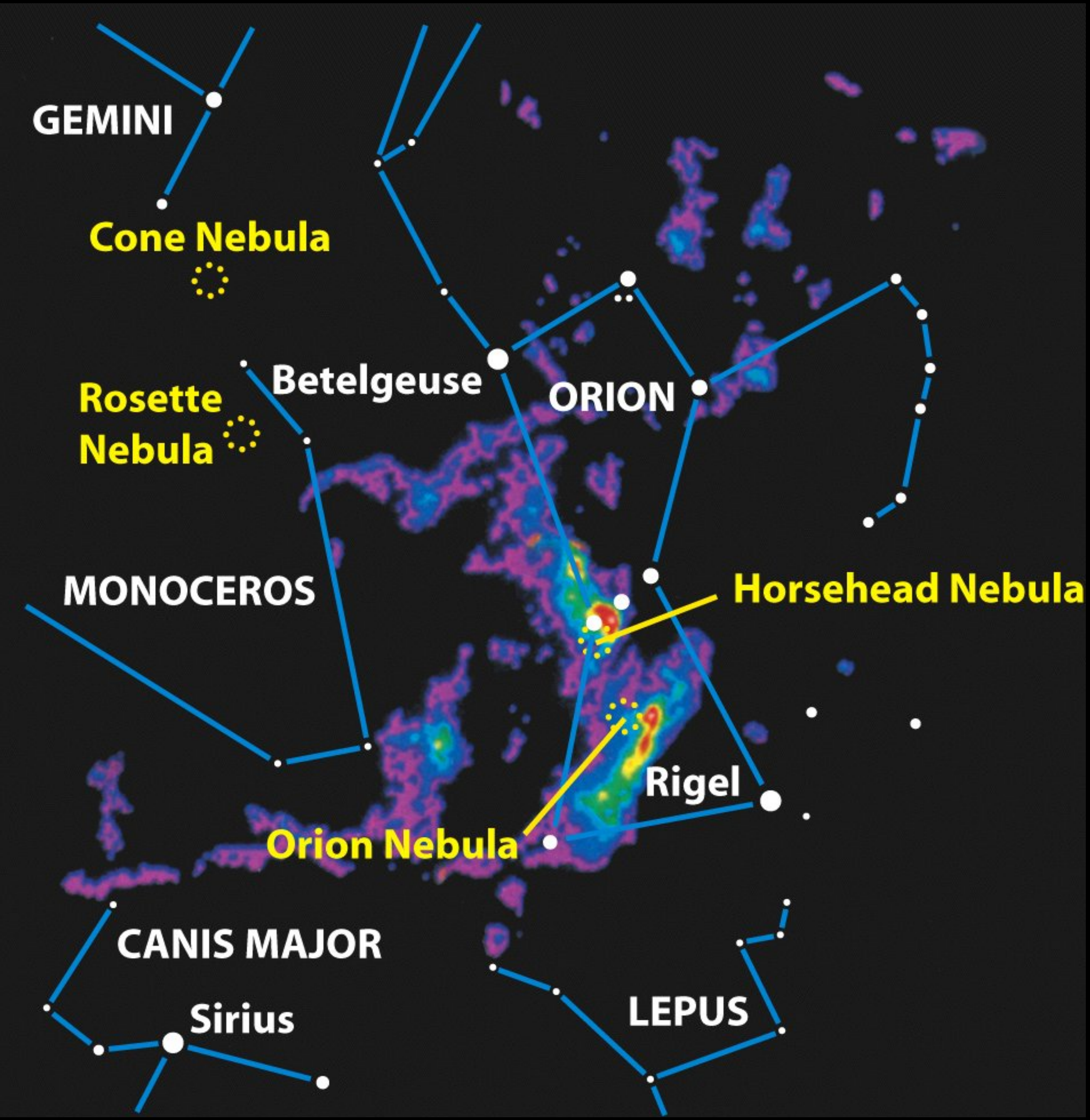


(b) An H-R diagram of the stars in the Pleiades

Star birth can begin in giant molecular clouds



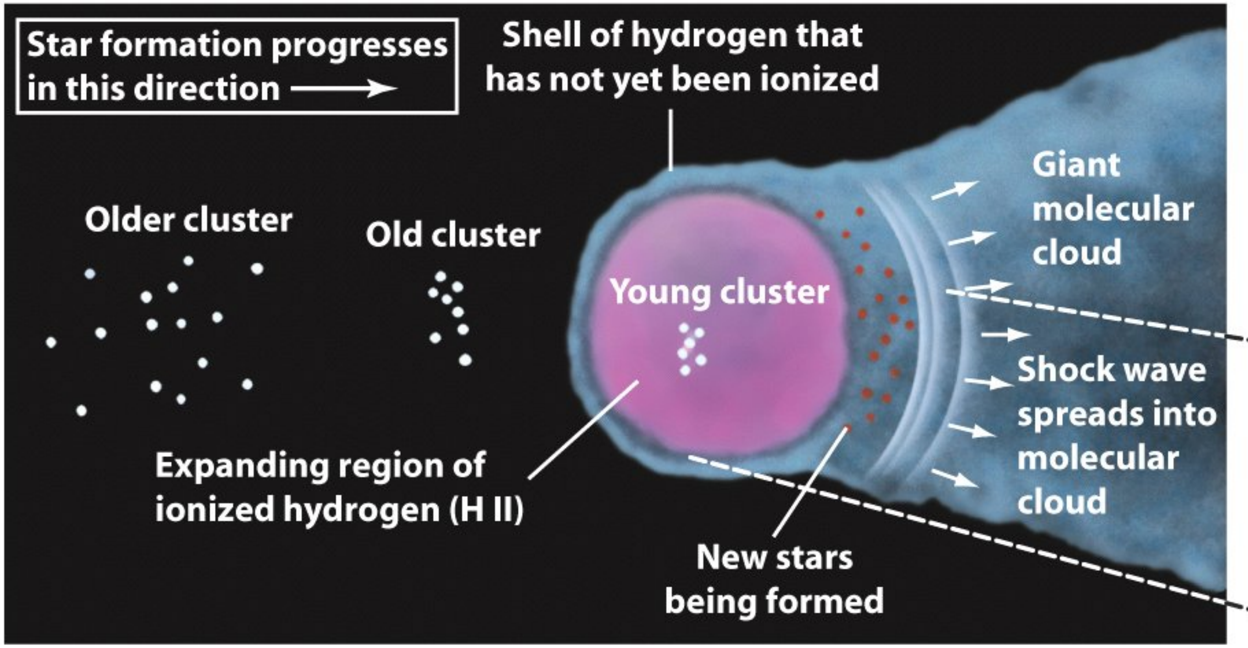
The spiral arms of our Galaxy are laced with giant molecular clouds, immense nebulae so cold that their constituent atoms can form into molecules

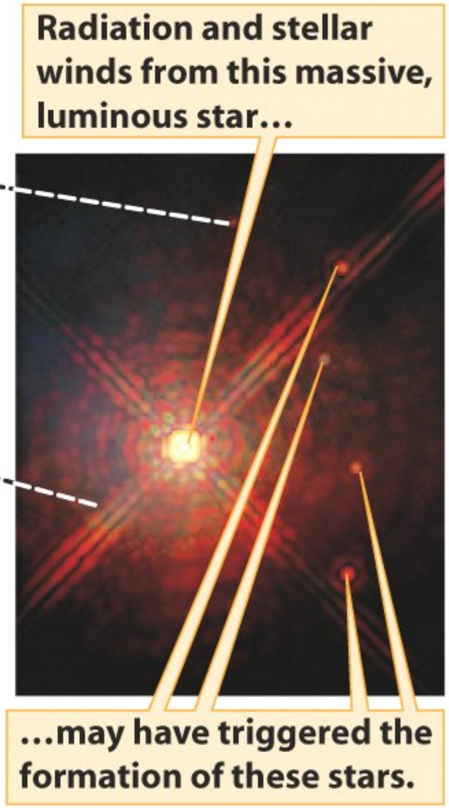


- Star-forming regions appear when a giant molecular cloud is compressed
- This can be caused by the cloud's passage through one of the spiral arms of our Galaxy, by a supernova explosion, or by other mechanisms

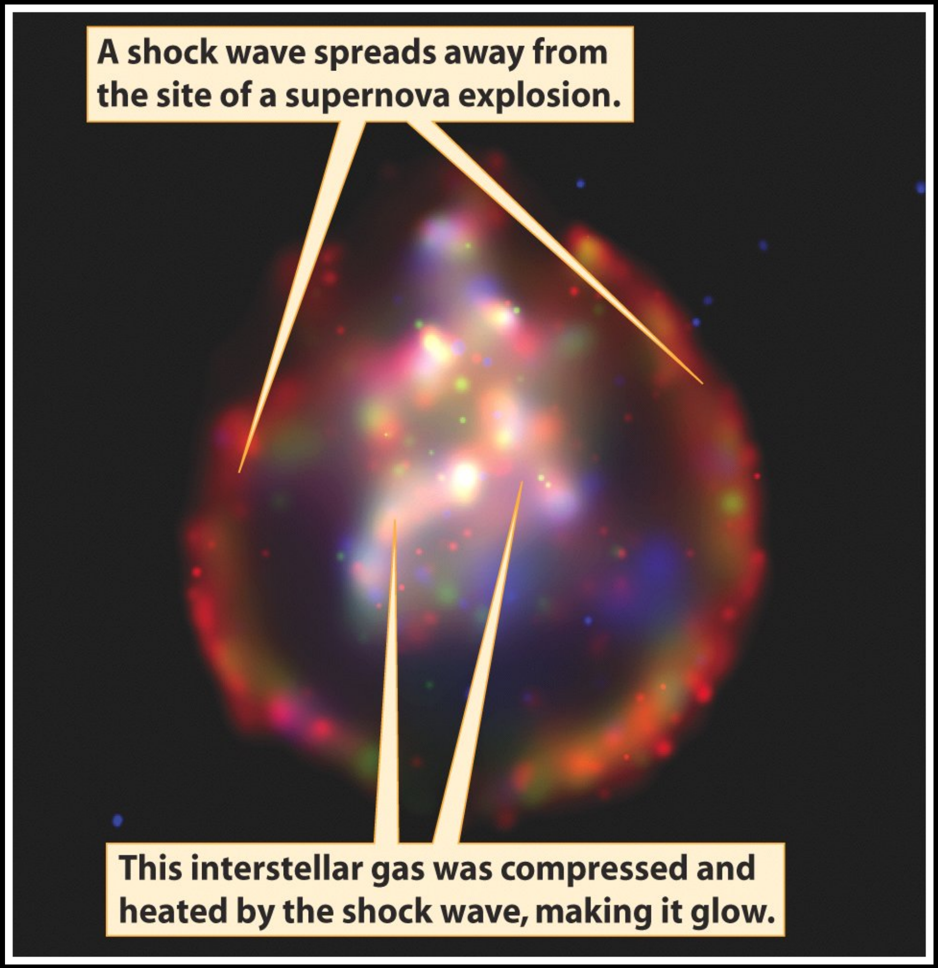
O and B Stars and Their Relation to H II Regions

- The most massive protostars to form out of a dark nebula rapidly become main sequence O and B stars
- They emit strong ultraviolet radiation that ionizes hydrogen in the surrounding cloud, thus creating the reddish emission nebulae called H II regions
- Ultraviolet radiation and stellar winds from the O and B stars at the core of an H II region create shock waves that move outward through the gas cloud, compressing the gas and triggering the formation of more protostars

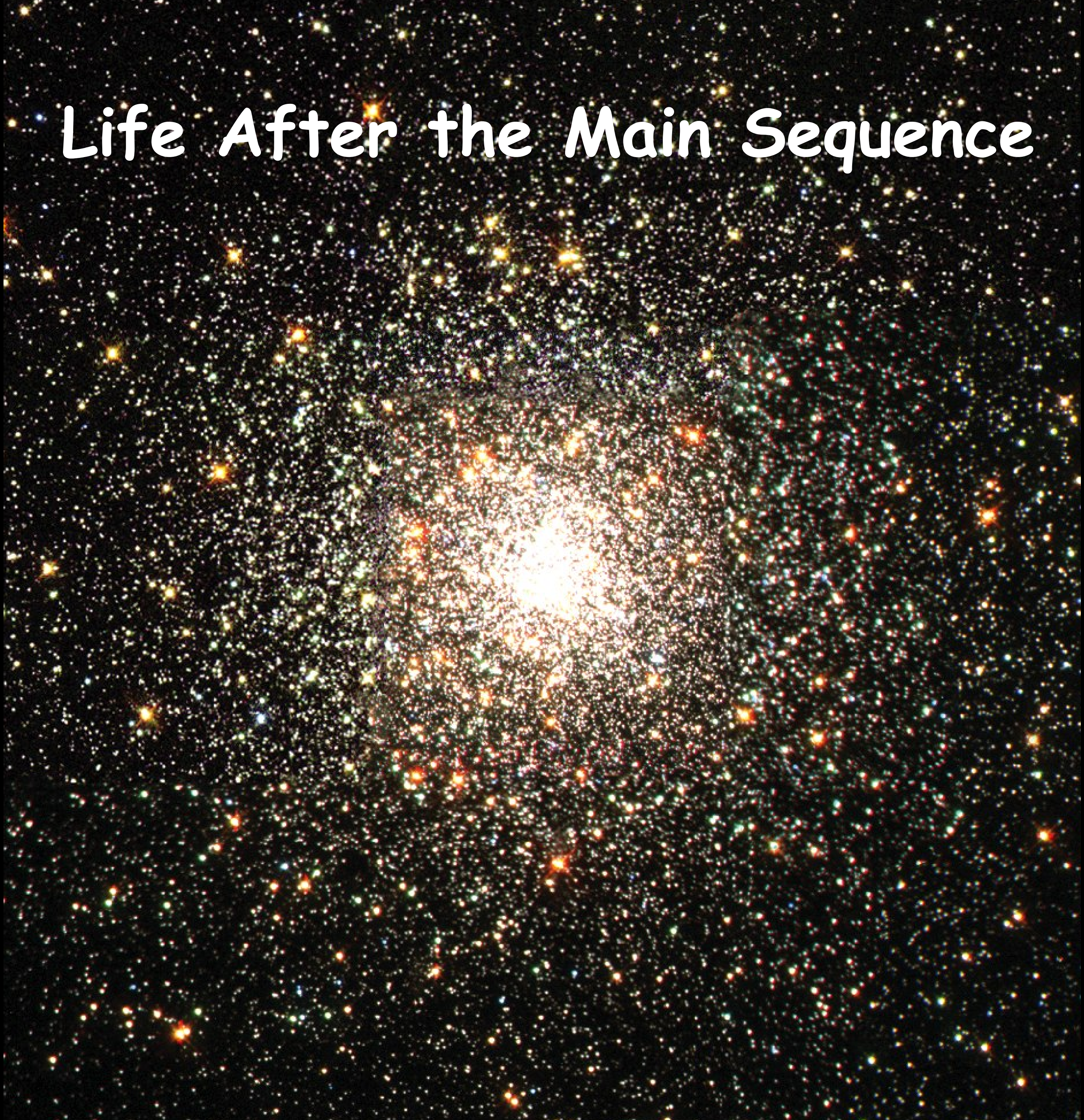

Star formation progresses in this direction
Shell of hydrogen that has not yet been ionized
Giant molecular cloud
Older cluster
Old cluster
Young cluster
Shock wave spreads into molecular cloud
Expanding region of ionized hydrogen (H II)
New stars being formed


Radiation and stellar winds from this massive, luminous star…
…may have triggered the formation of these stars.

Supernovae can compress the interstellar medium and trigger star birth



Life After the Main Sequence



Guiding Questions

1. How will our Sun change over the next few billion years?
2. Why are red giants larger than main-sequence stars?
3. Do all stars evolve into red giants at the same rate?
4. How do we know that many stars lived and died before our Sun was born?
5. Why do some giant stars pulsate in and out?
6. Why do stars in some binary systems evolve in unusual ways?

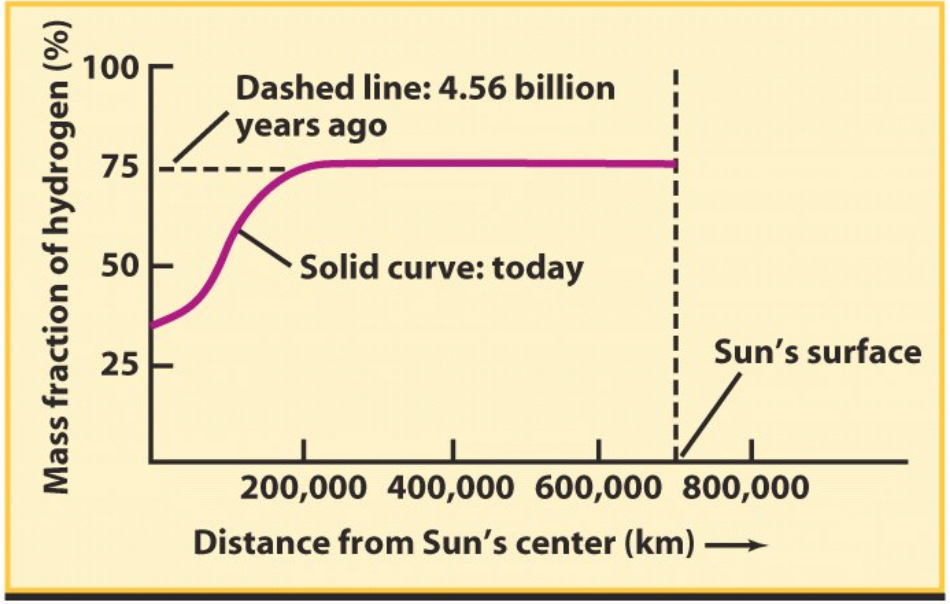
A star’s lifetime on the main sequence is proportional to its mass divided by its luminosity

Approximate Main-Sequence Lifetimes

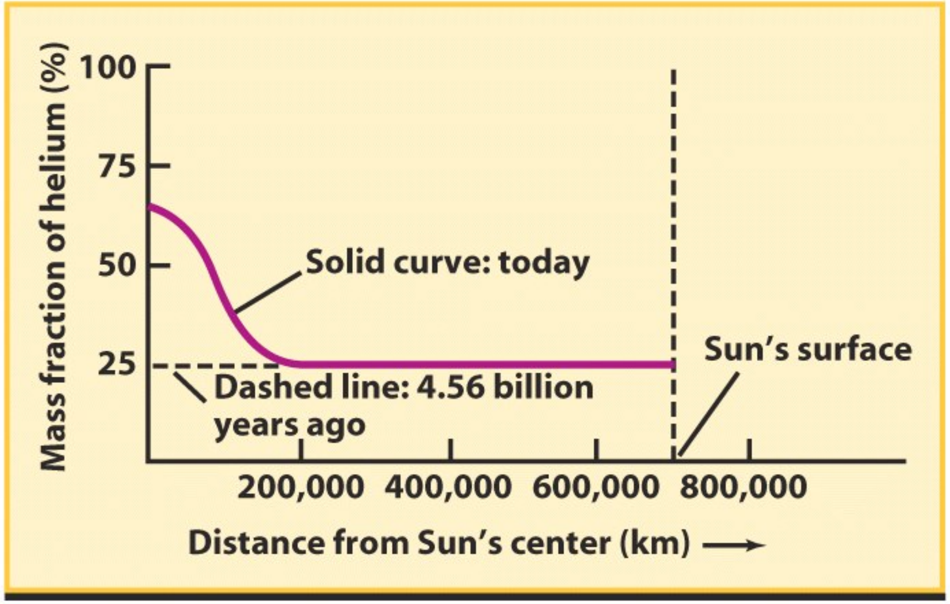
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

- The duration of a star’s main sequence lifetime depends on the amount of hydrogen in the star’s core and the rate at which the hydrogen is consumed
- N.B. - The **more massive** a star, **the shorter** is its main-sequence lifetime

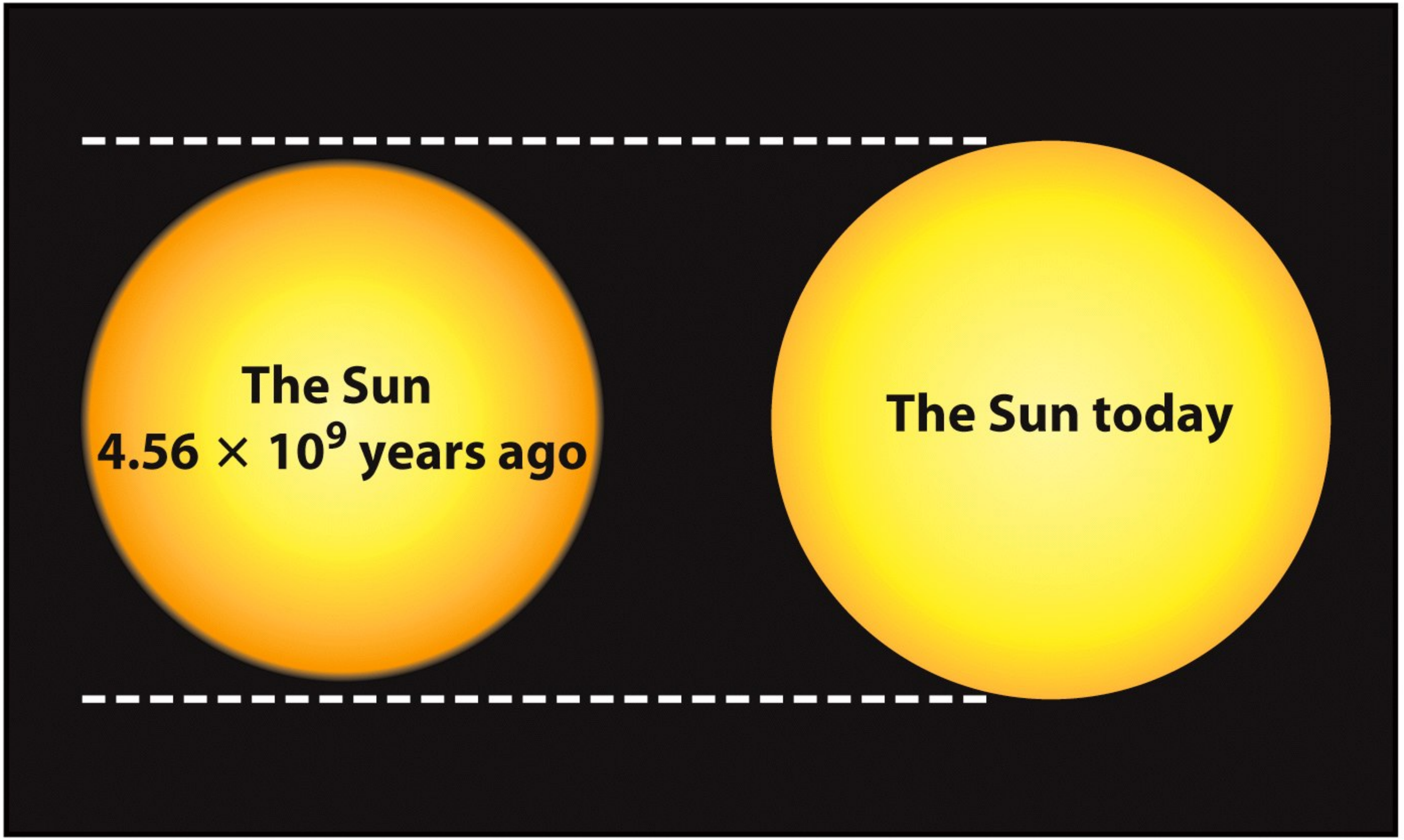


(a) Hydrogen in the Sun's interior



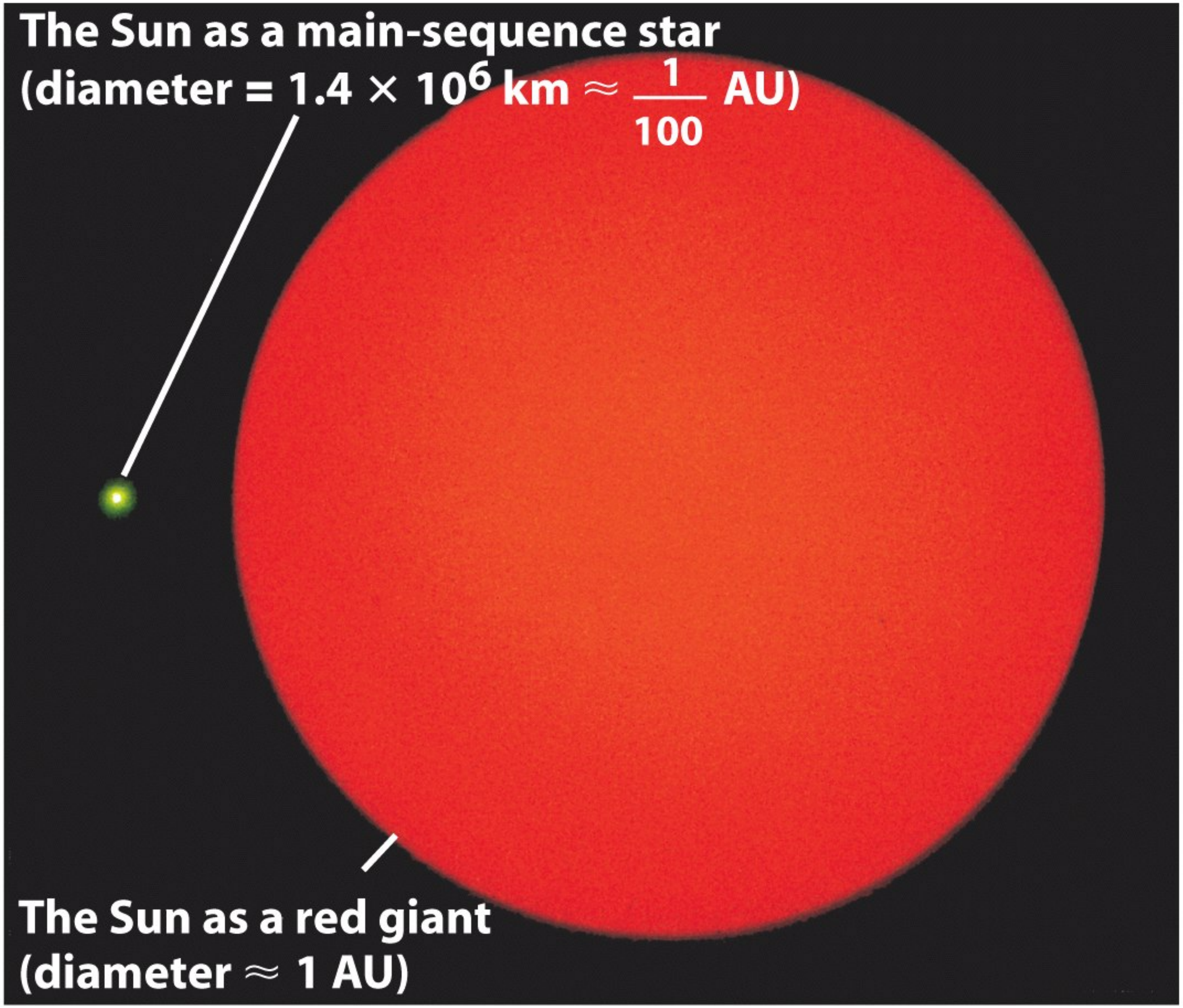
(b) Helium in the Sun's interior

The Sun has been a main-sequence star for about 4.56 billion years and should remain one for about another 7 billion years



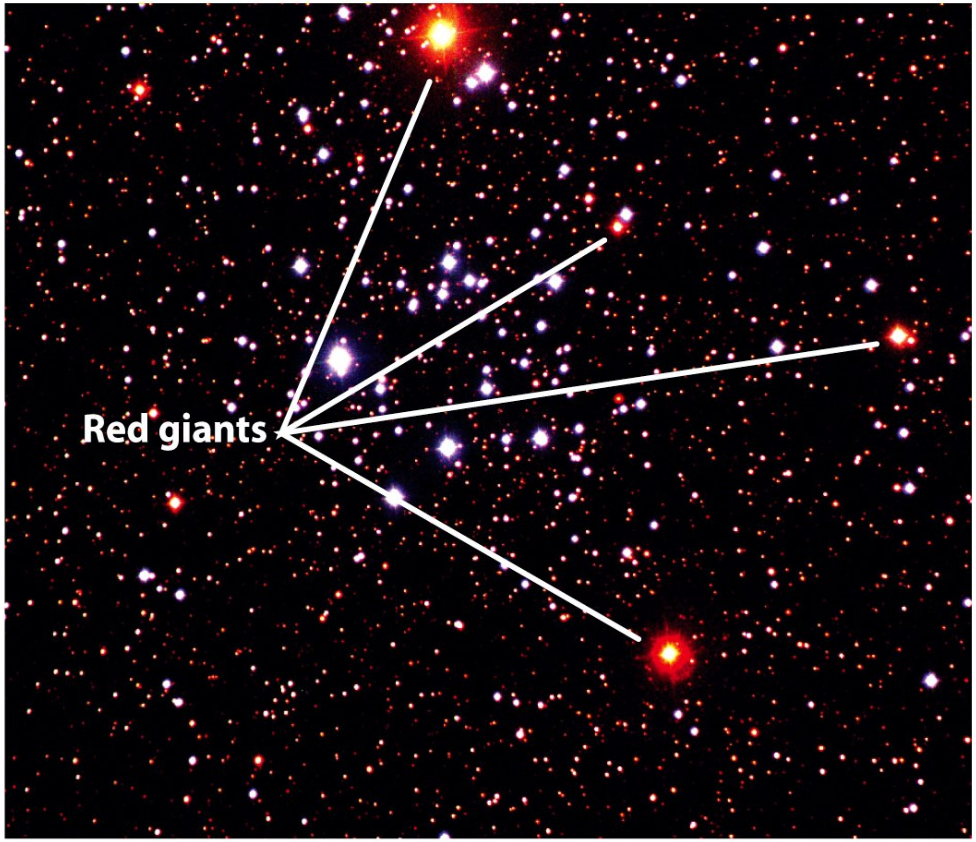
During a star's main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity

When core hydrogen fusion ceases, a main-sequence star becomes a red giant



The Sun today and as a red giant

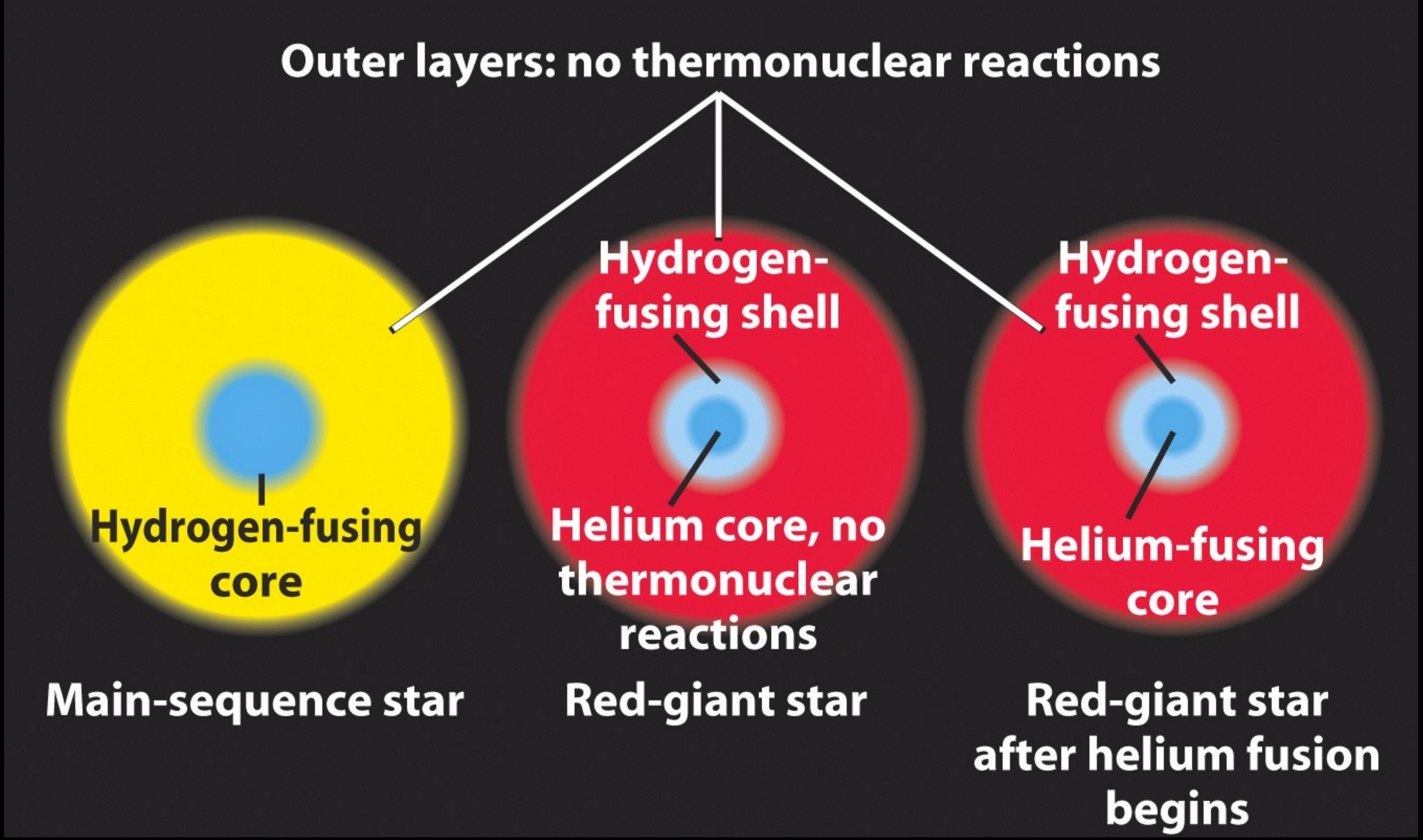
Red Giants



Red giant stars in the star cluster M50

- Core hydrogen fusion ceases when the hydrogen has been exhausted in the core of a main-sequence star
- This leaves a core of nearly pure helium surrounded by a shell through which hydrogen fusion works its way outward in the star
- The core shrinks and becomes hotter, while the star's outer layers expand and cool
- The result is a red giant star

As stars age and become giant stars, they expand and shed matter into space



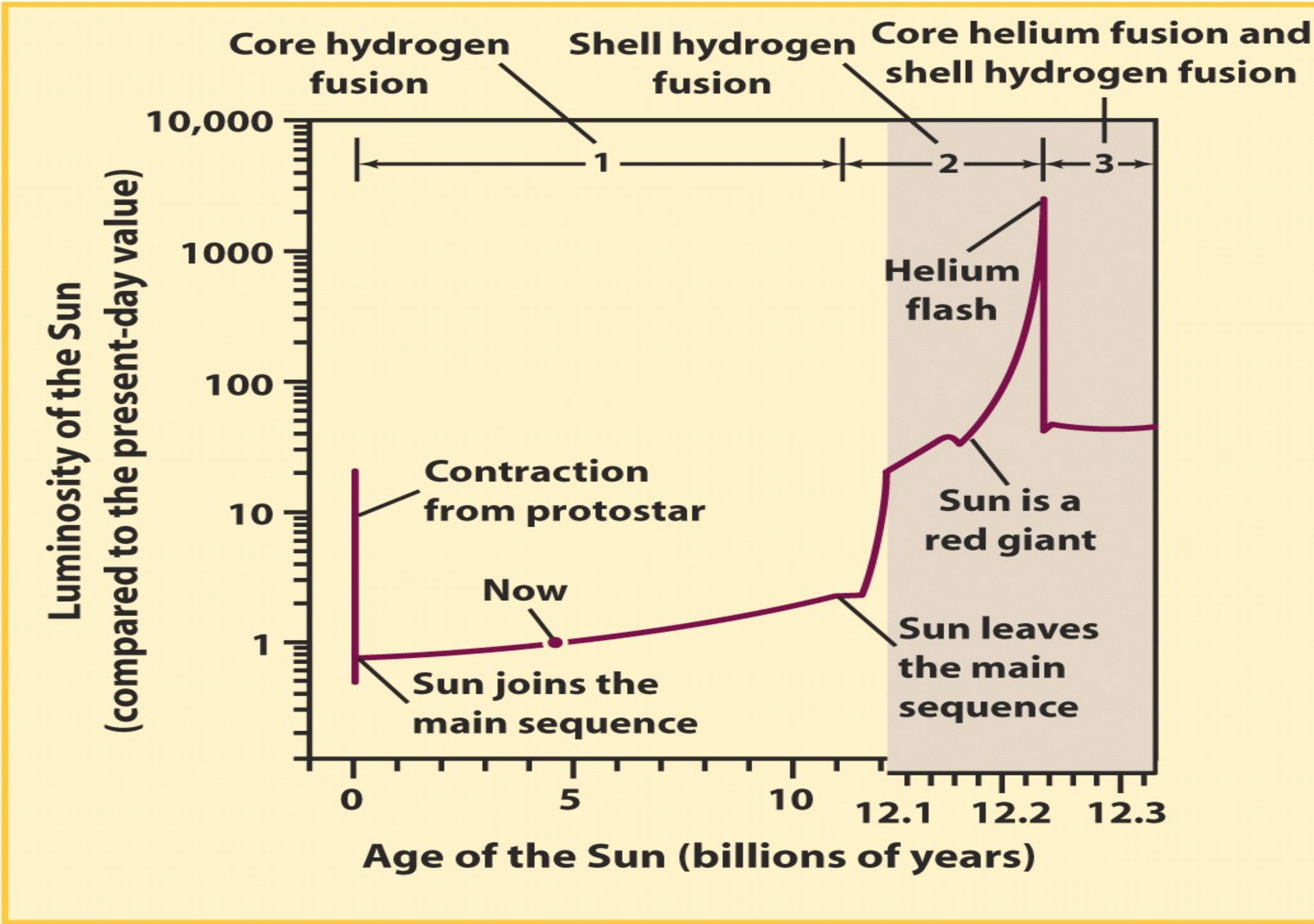
- When the central temperature of a red giant reaches about 100 million K, helium fusion begins in the core.
- A process called the triple alpha process, converts helium to carbon and oxygen.

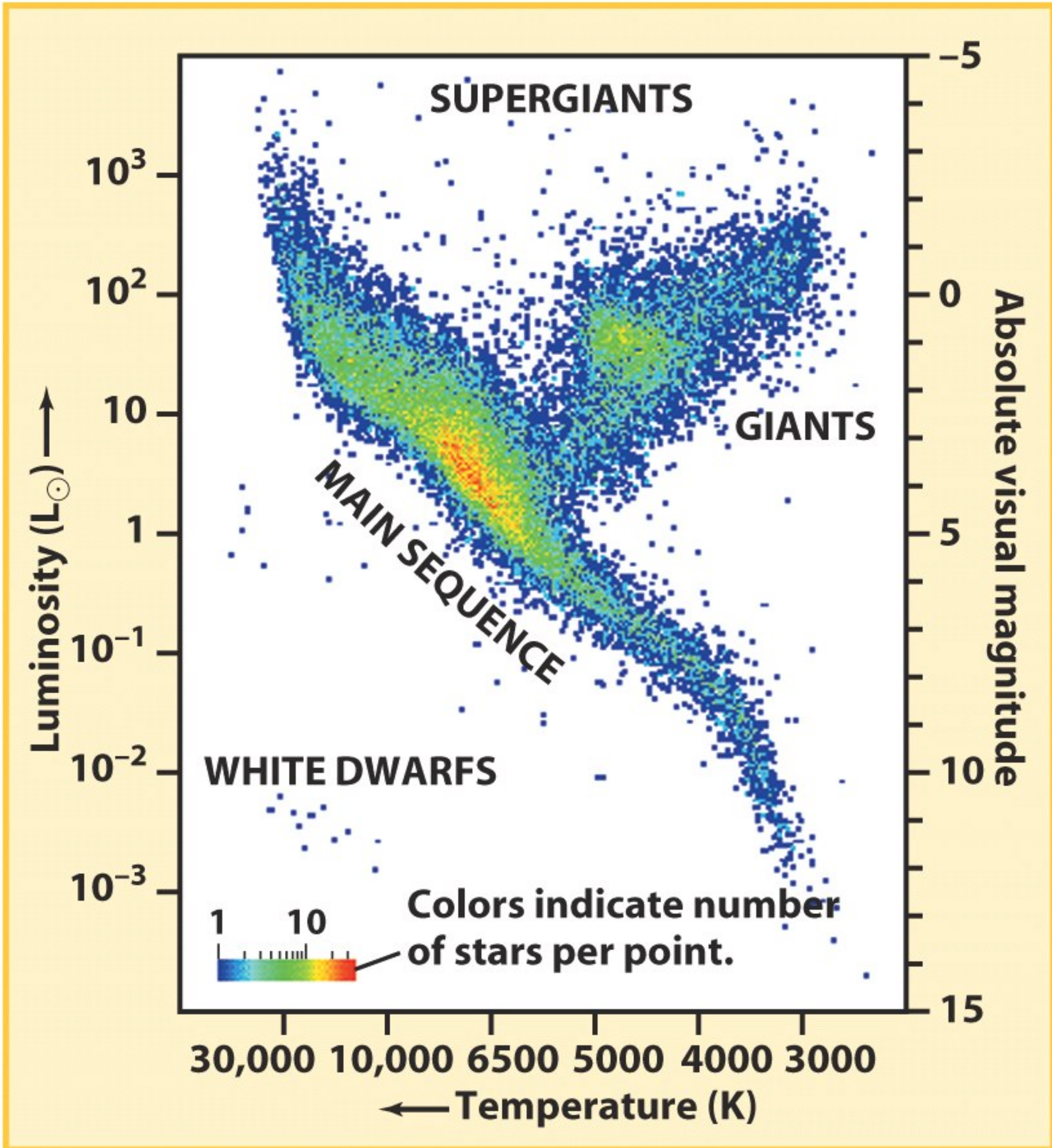
How Helium Core Fusion Begins in Different Red Giants

Mass of star	Onset of helium burning in core
Less than 2–3 solar masses	Explosive (helium flash)
More than 2–3 solar masses	Gradual

- In a more massive red giant, helium fusion begins gradually
- In a less massive red giant, it begins suddenly, in a process called the helium flash

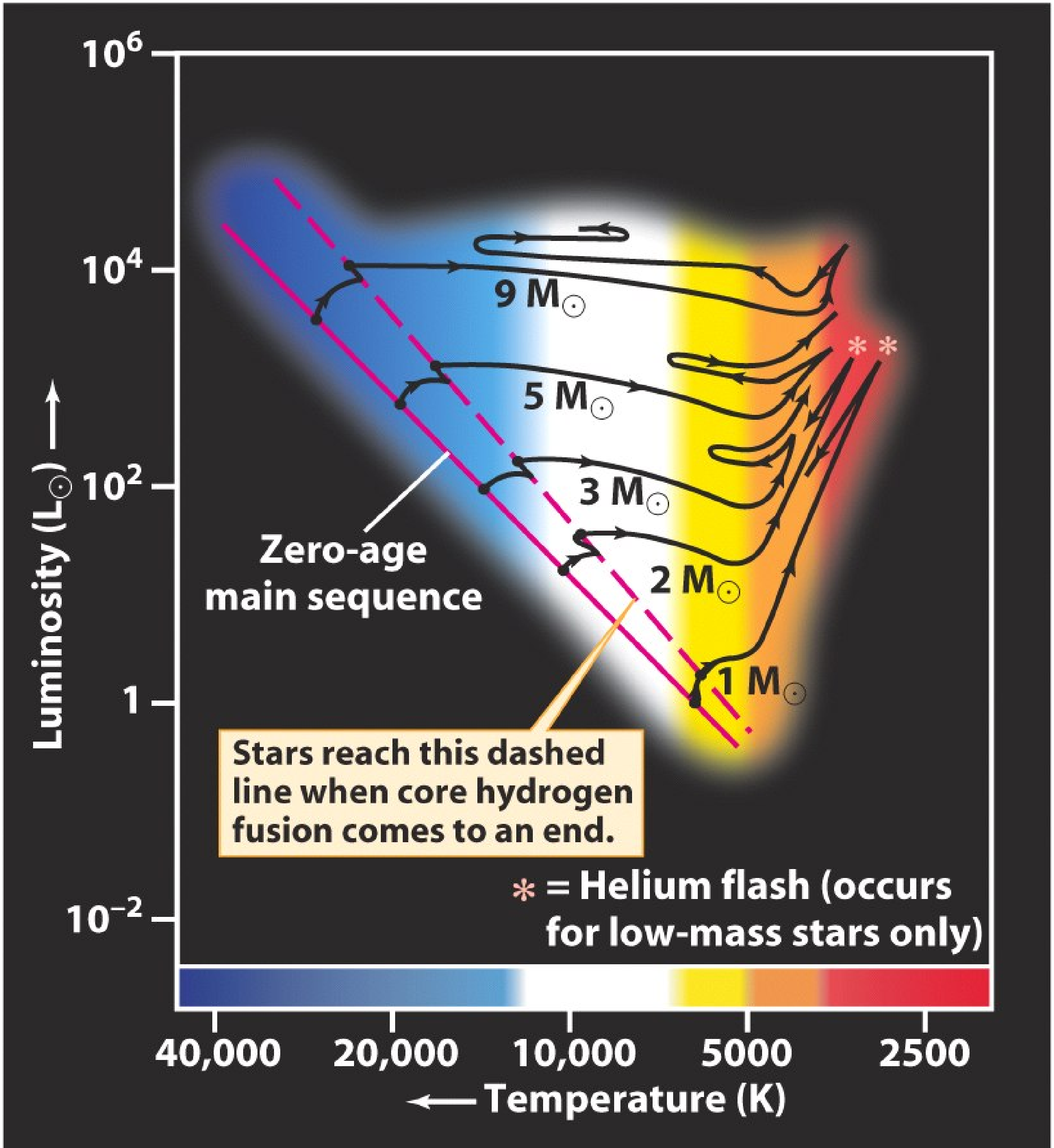
After helium flash, a low-mass star moves quickly from the red-giant region of the H-R diagram to the horizontal branch





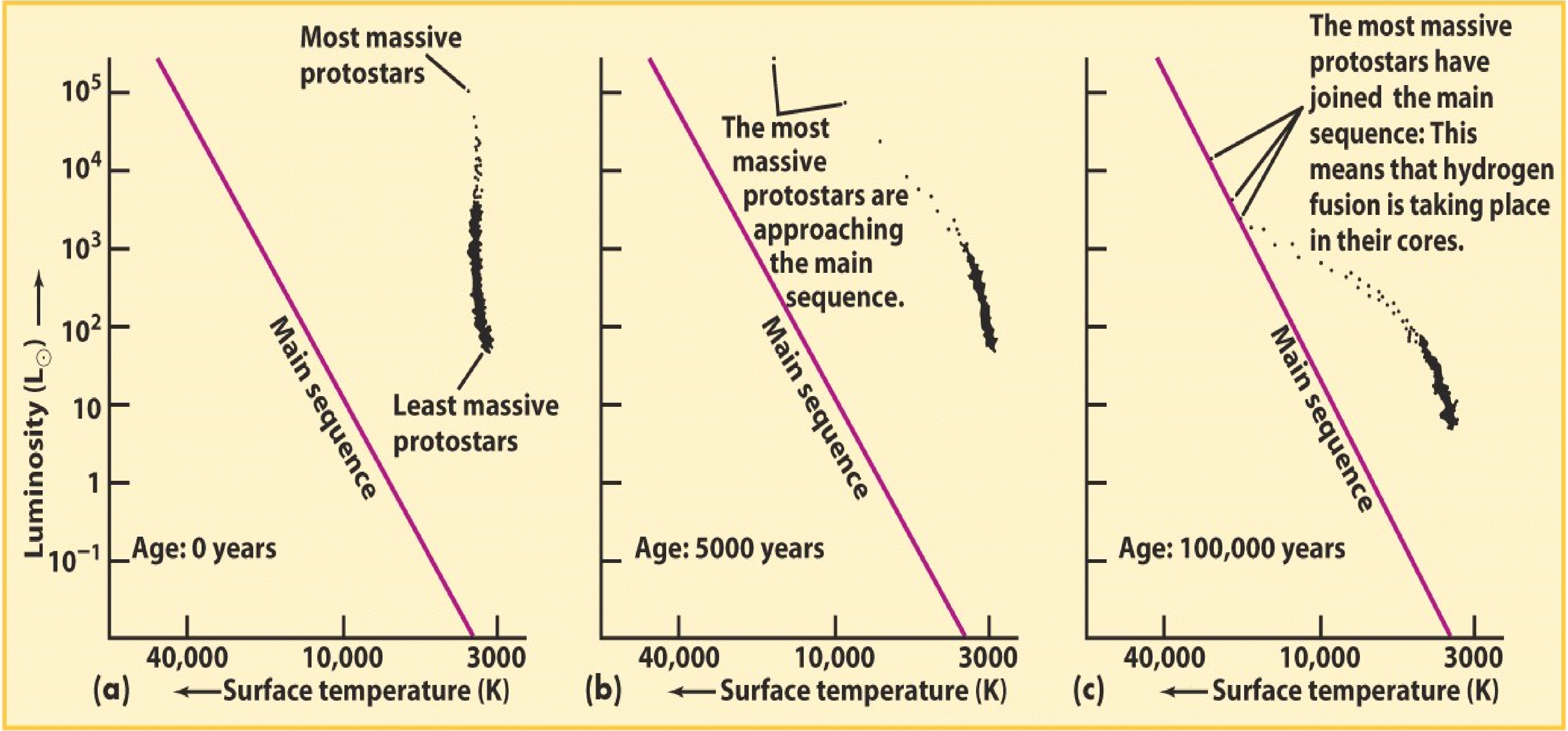
H-R diagram of 20,853 stars—note the width of the main sequence

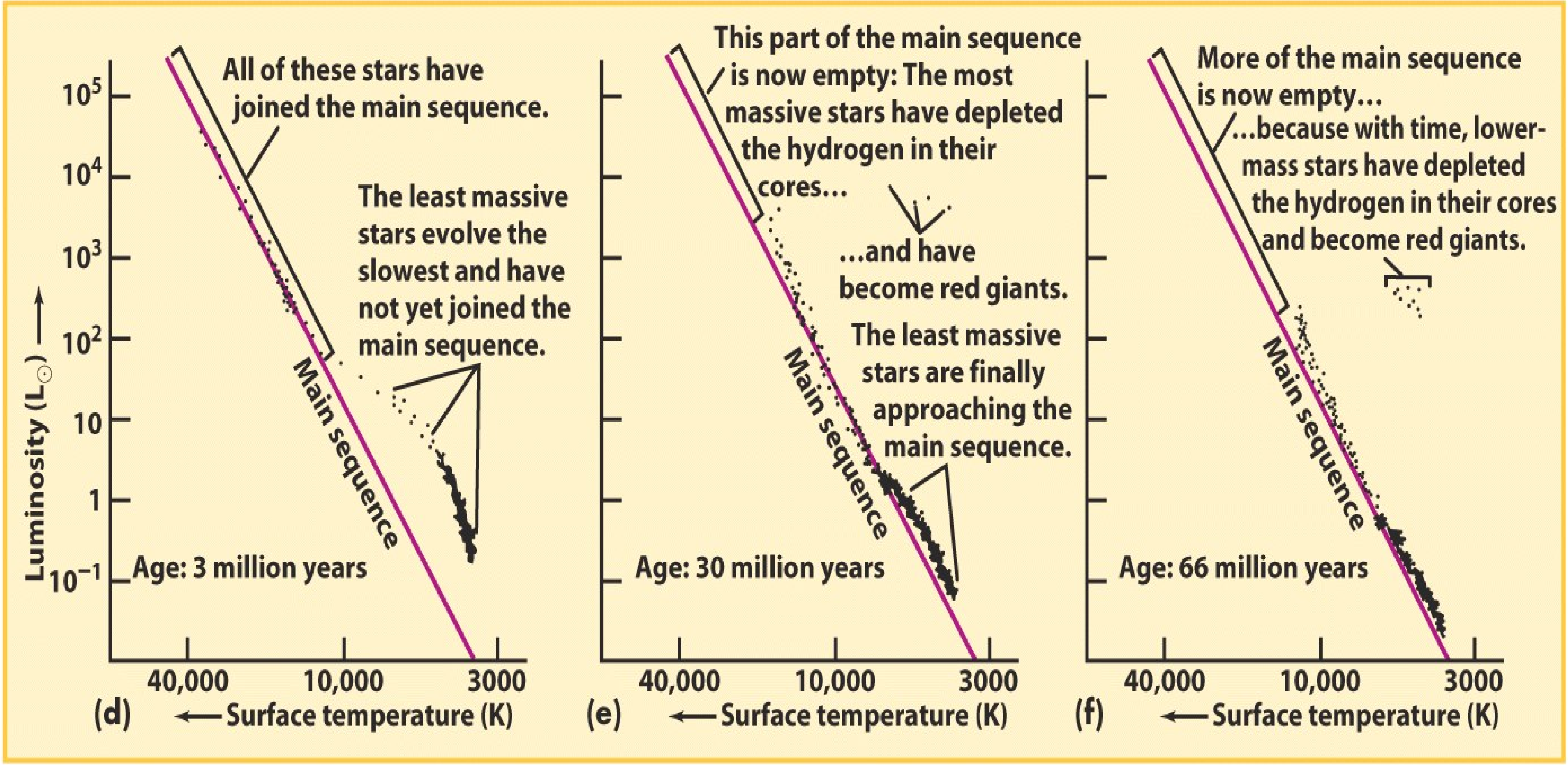
- H-R diagrams and observations of star clusters reveal how red giants evolve
- The age of a star cluster can be estimated by plotting its stars on an H-R diagram



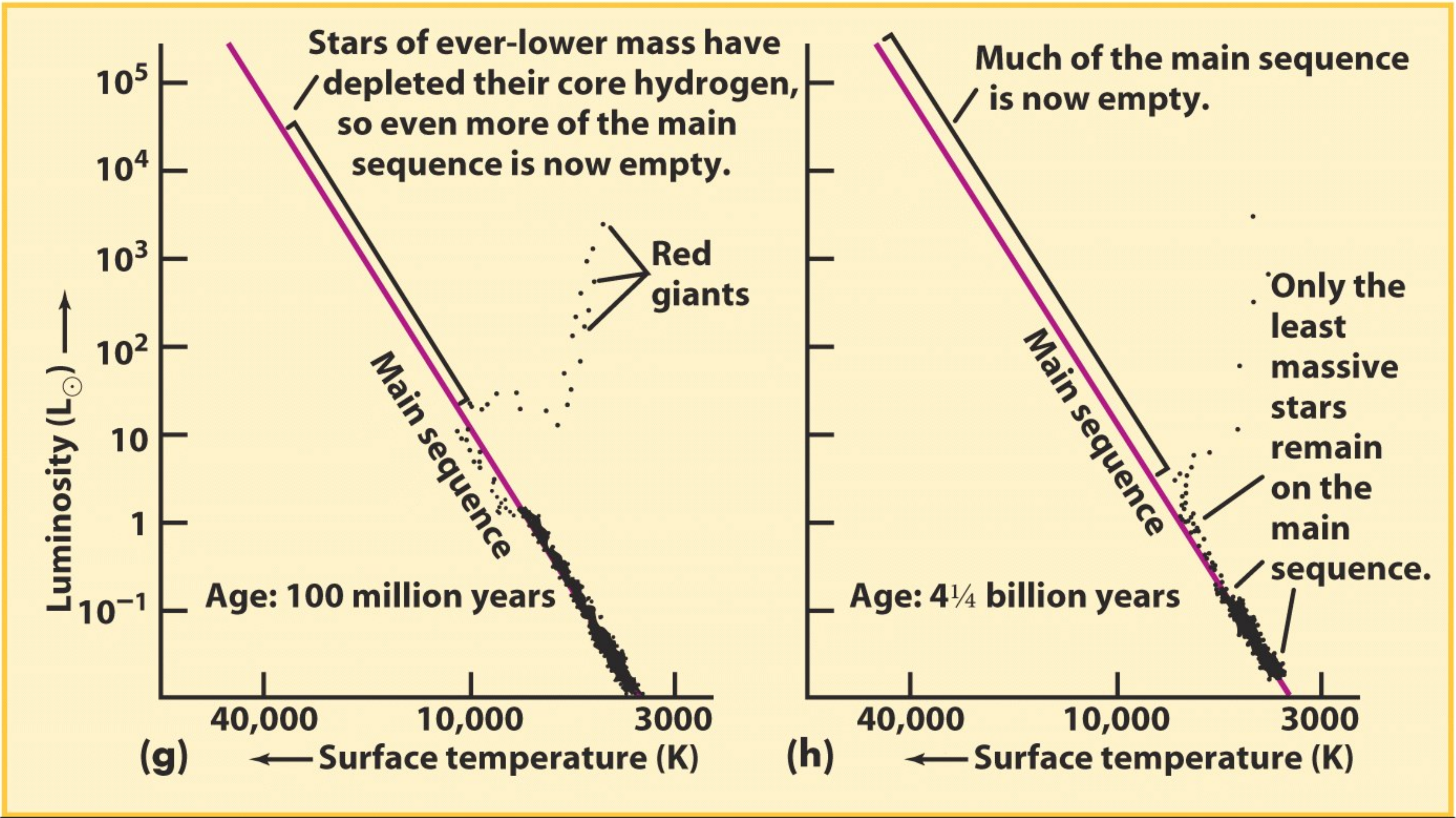
Post–main-sequence evolutionary tracks of five stars with different mass

The cluster's age can be estimated by the age of the main-sequence stars at the turnoff point (the upper end of the remaining main sequence)



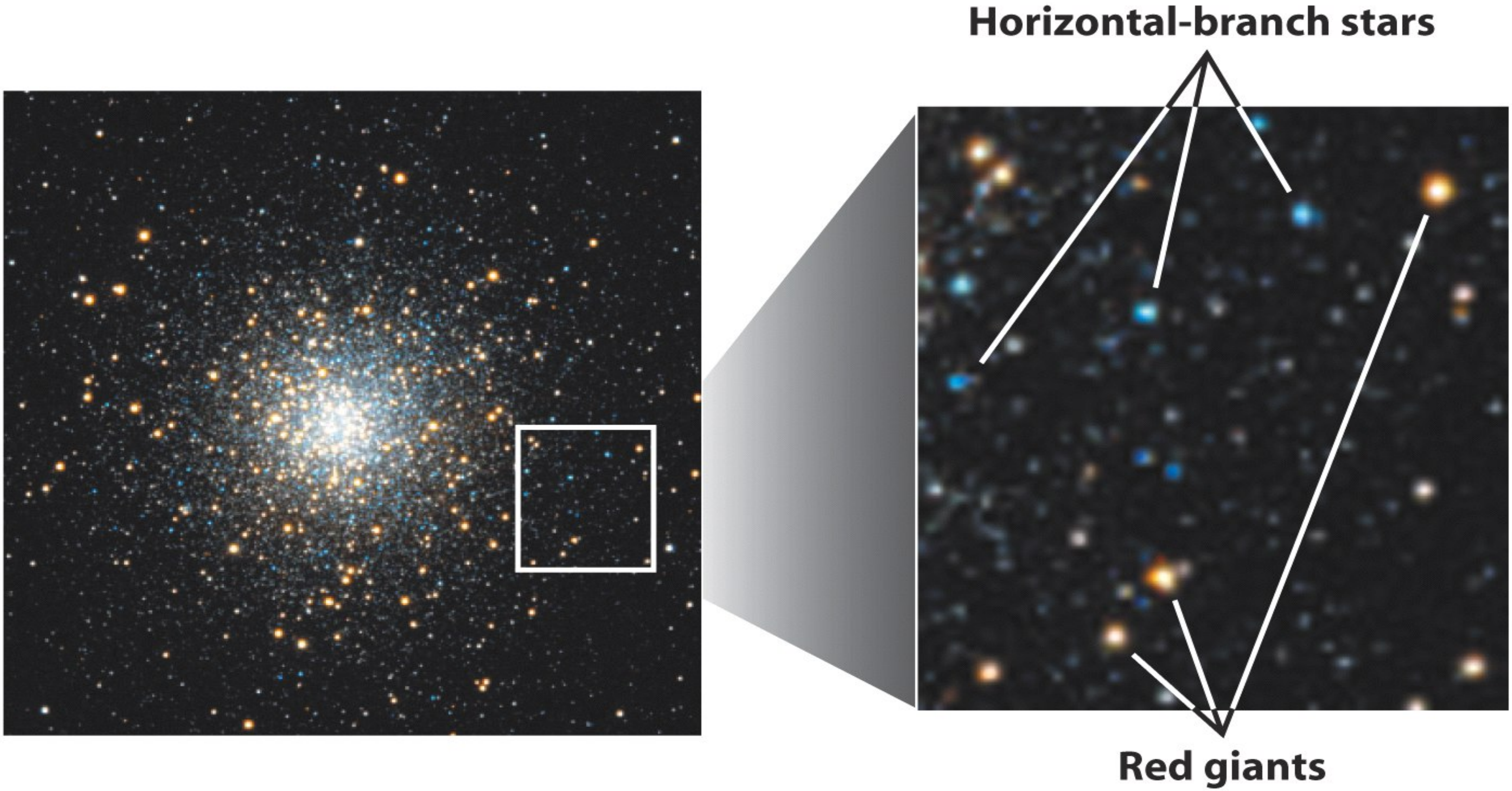


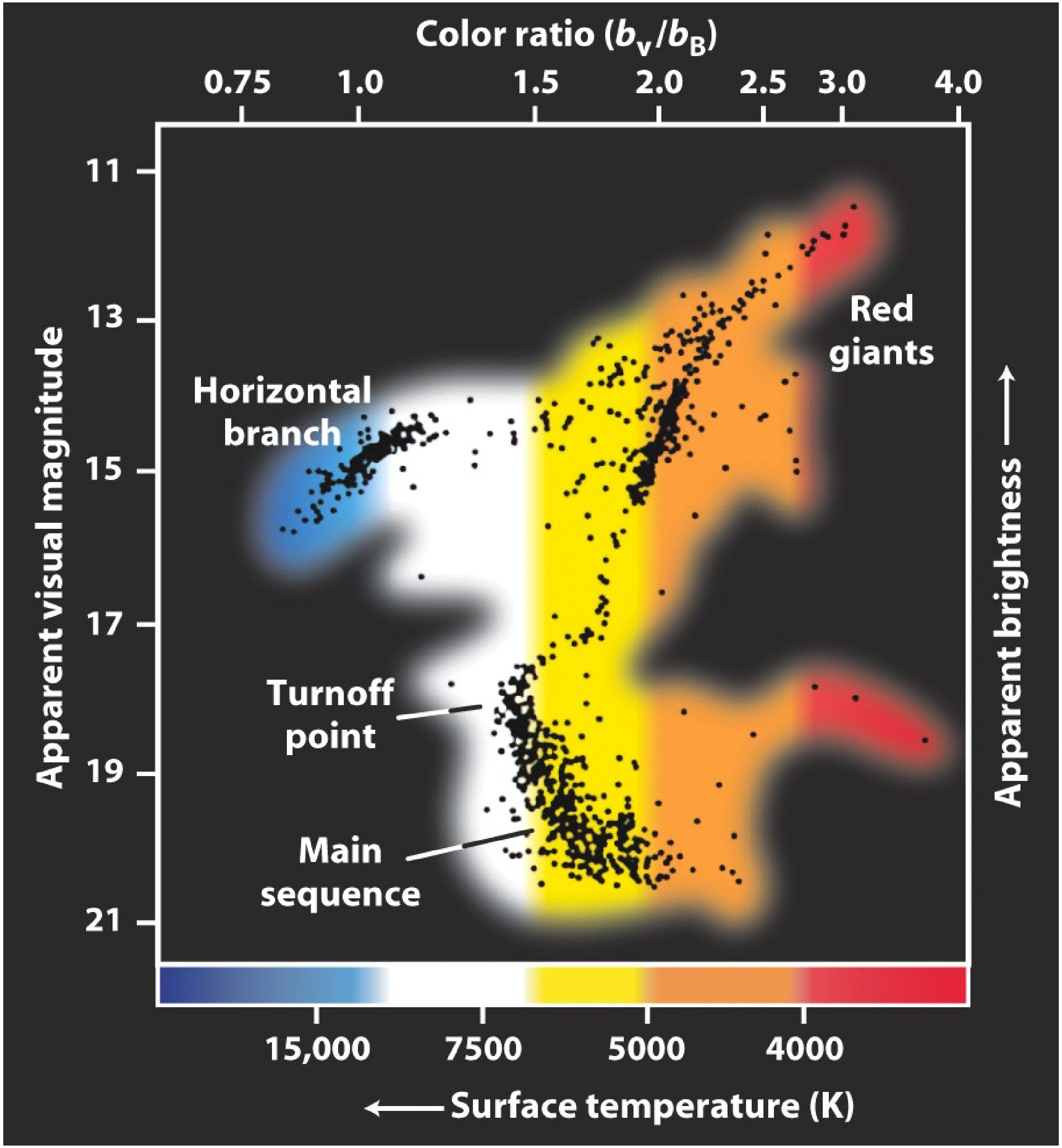
All of these stars have joined the main sequence.
The least massive stars evolve the slowest and have not yet joined the main sequence.
Main sequence
10^5
10^4
10^3
10^2
10
1
10^{-1}
Luminosity ($L_\odot$)
Age: 3 million years
40,000
10,000
3000
(d)
Surface temperature (K)
This part of the main sequence is now empty: The most massive stars have depleted the hydrogen in their cores…
…and have become red giants.
The least massive stars are finally approaching the main sequence.
Main sequence
Age: 30 million years
40,000
10,000
3000
(e)
Surface temperature (K)
More of the main sequence is now empty…
…because with time, lower-mass stars have depleted the hydrogen in their cores and become red giants.
Main sequence
Age: 66 million years
40,000
10,000
3000
(f)
Surface temperature (K)



Stars of ever-lower mass have depleted their core hydrogen, so even more of the main sequence is now empty.
10^5
10^4
10^3
10^2
10
1
10^{-1}
Luminosity ($L_\odot$)
Red giants
Main sequence
Age: 100 million years
40,000
10,000
3000
(g)
Surface temperature (K)
Much of the main sequence is now empty.
Only the least massive stars remain on the main sequence.
Main sequence
Age: 4¼ billion years
40,000
10,000
3000
(h)
Surface temperature (K)

As a cluster ages, the main sequence is “eaten away” from the upper left as stars of progressively smaller mass evolve into red giants




Color ratio (b_V/b_B)
0.75
1.0
1.5
2.0
2.5
3.0
4.0
11
13
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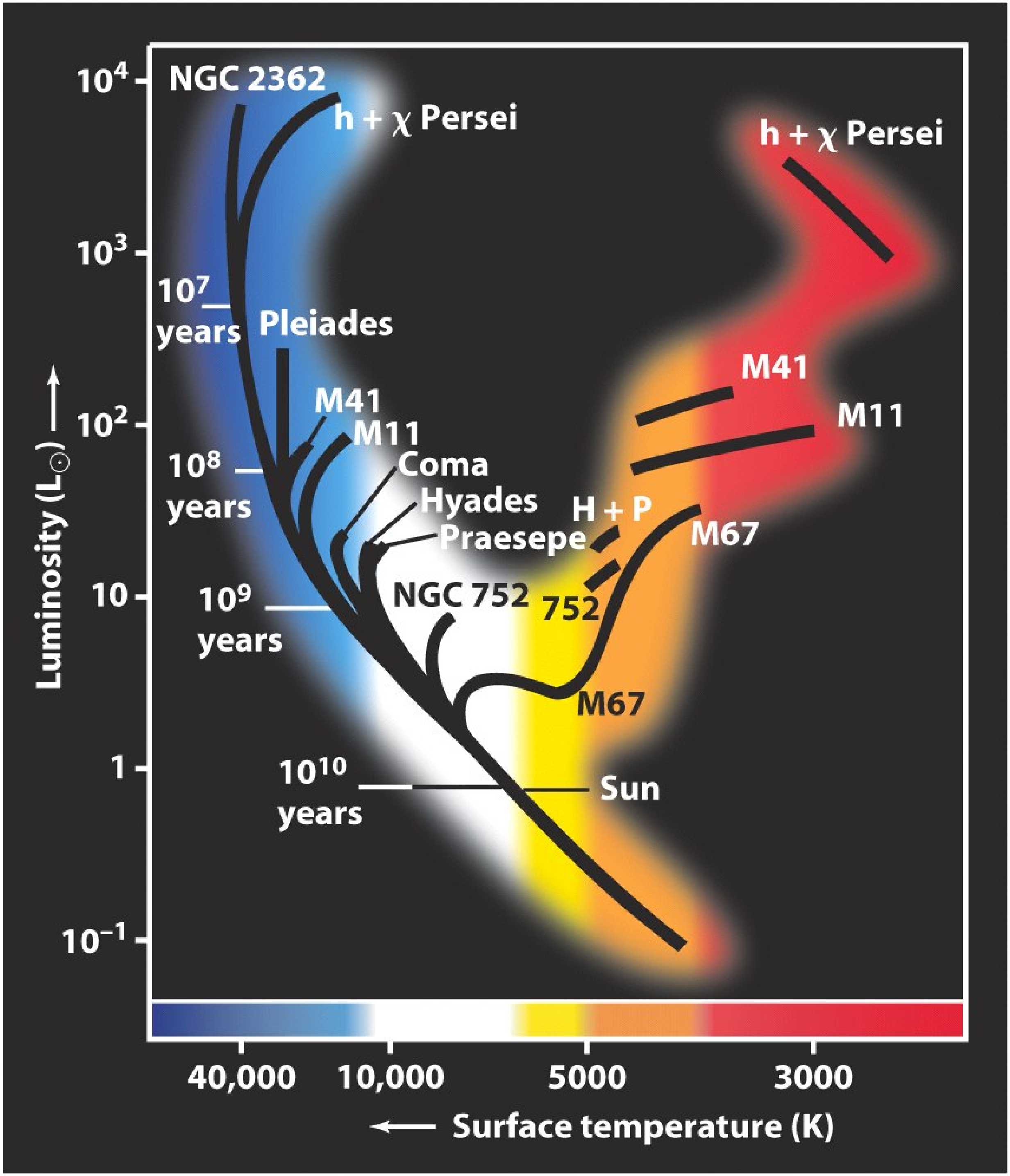
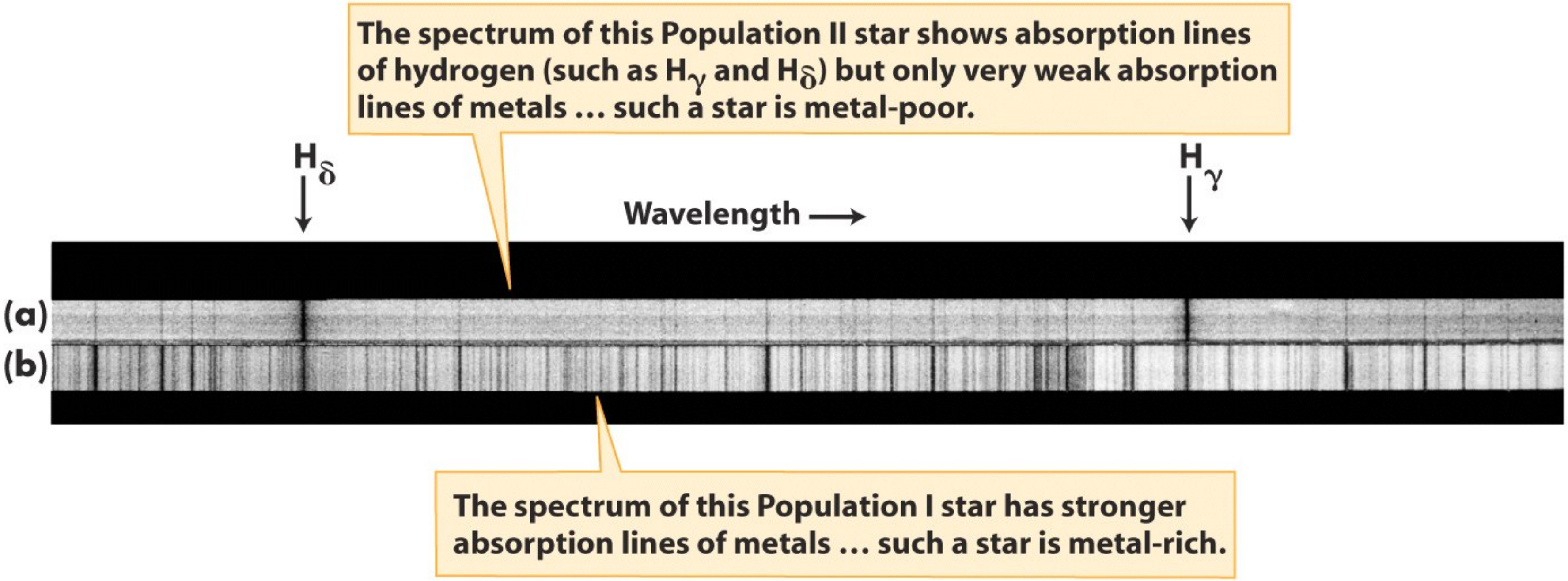
21
Apparent visual magnitude
Horizontal branch
Red giants
Turnoff point
Main sequence
Apparent brightness
15,000
7500
5000
4000
Surface temperature (K)

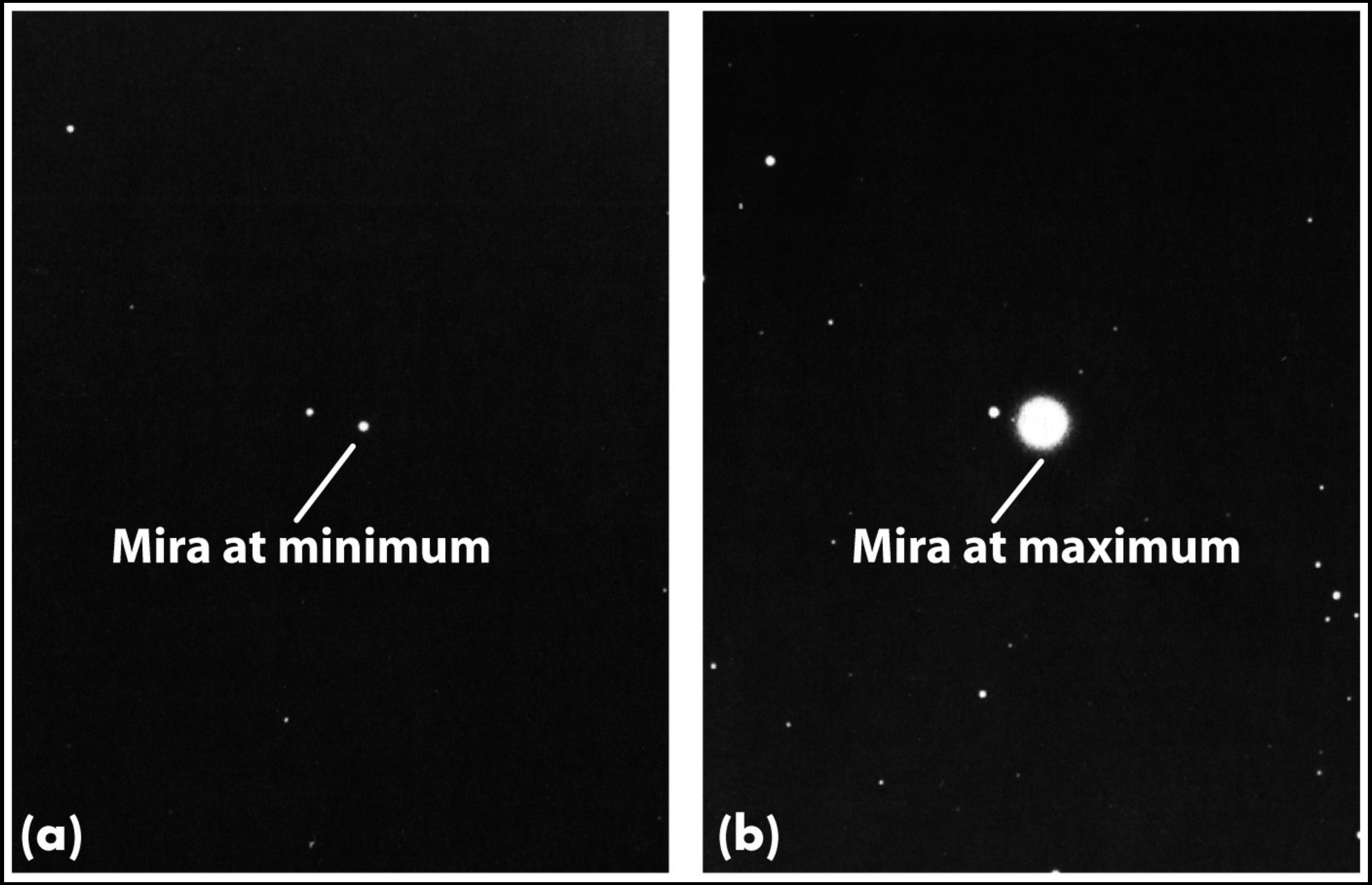

NGC 2362
h + χ Persei
h + χ Persei
10^4
10^3
10^2
10
1
10^{-1}
10^7 years
Pleiades
M41
M11
10^8 years
Coma
Hyades
H + P
Praesepe
M41
M11
M67
10^9 years
NGC 752
752
M67
10^{10} years
Sun
Luminosity ($L_\odot$)
40,000
10,000
5000
3000
Surface temperature (K)

Populations (generations) of stars

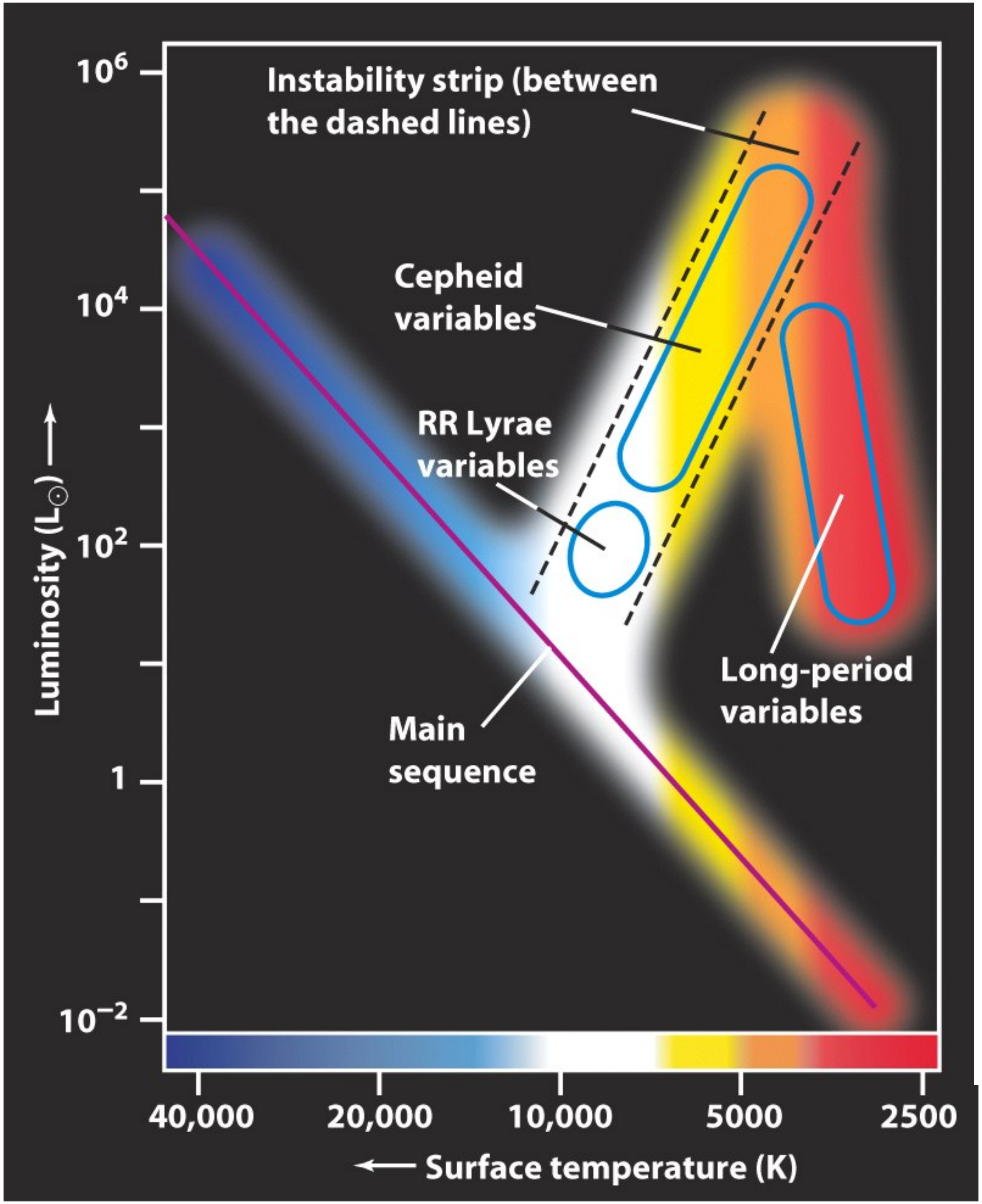


- Relatively young Population I stars are metal rich; ancient Population II stars are metal poor
- The metals (heavy elements) in Population I stars were manufactured by thermonuclear reactions in an earlier generation of Population II stars, then ejected into space and incorporated into a later stellar generation

Variable Stars

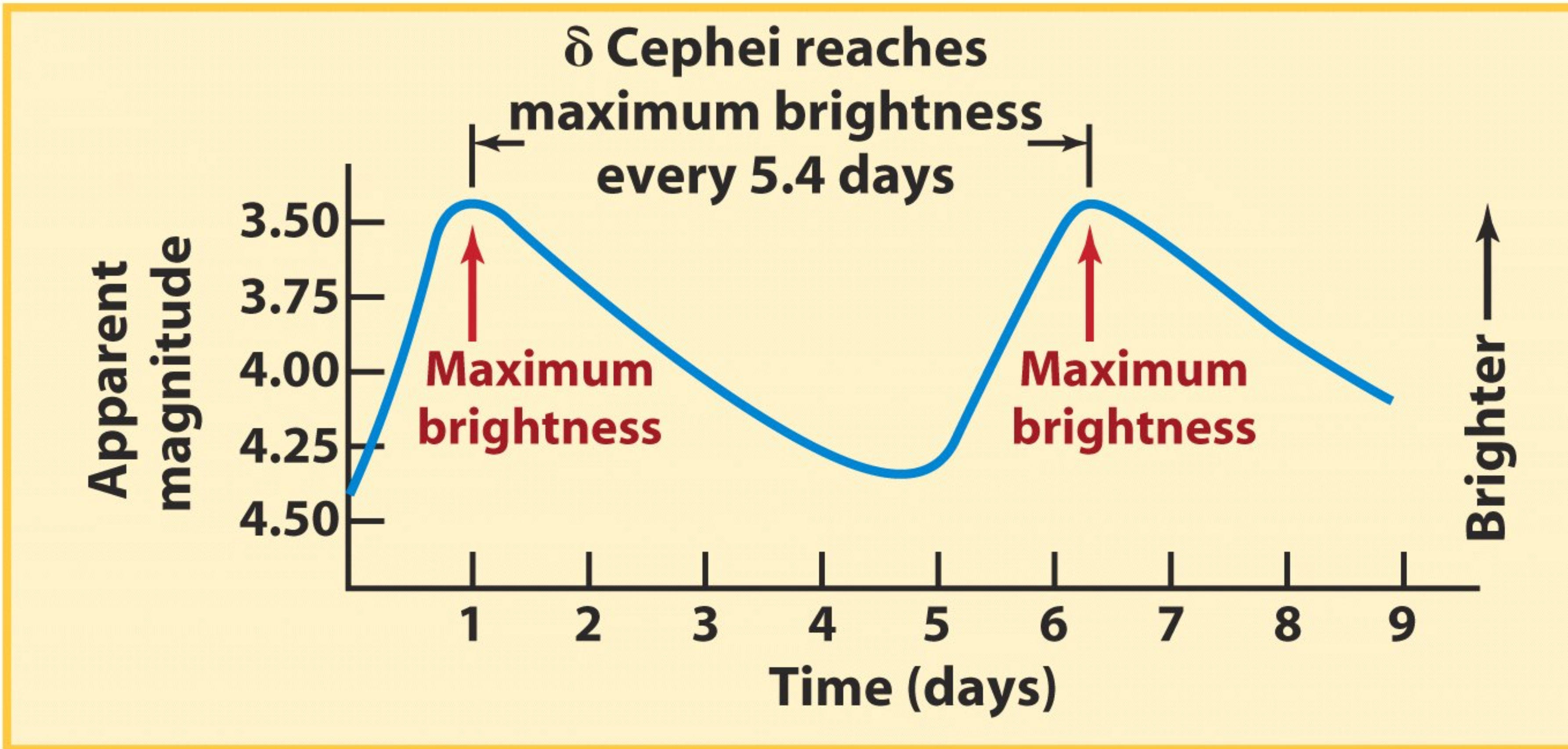


When a star's evolutionary track carries it through a region in the H-R diagram called the instability strip, the star becomes unstable and begins to pulsate

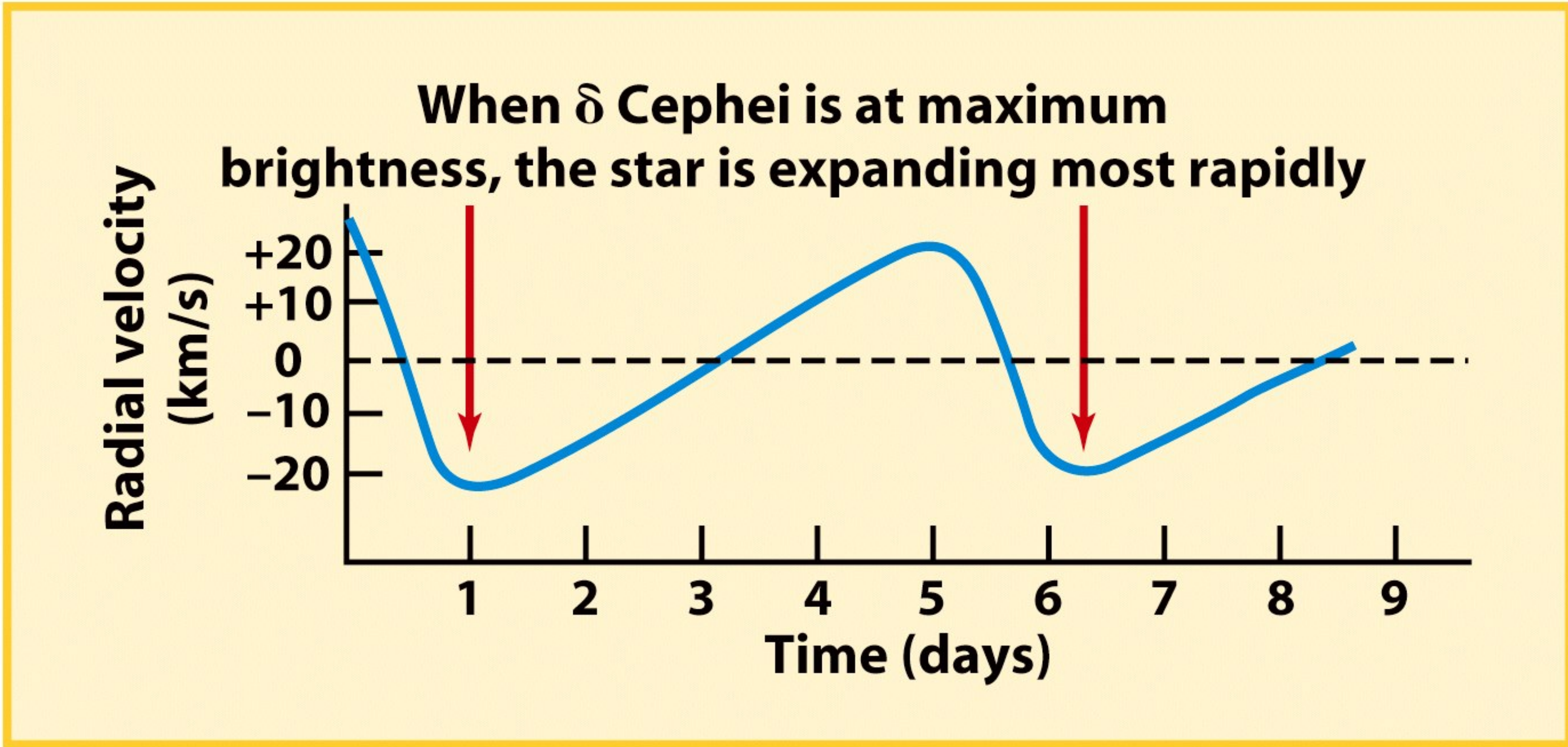


- Cepheid variables are high-mass variable stars
- RR Lyrae variables are lower-mass, metal-poor variable stars with short periods
- Long-period variable stars also pulsate but in a fashion that is less well understood

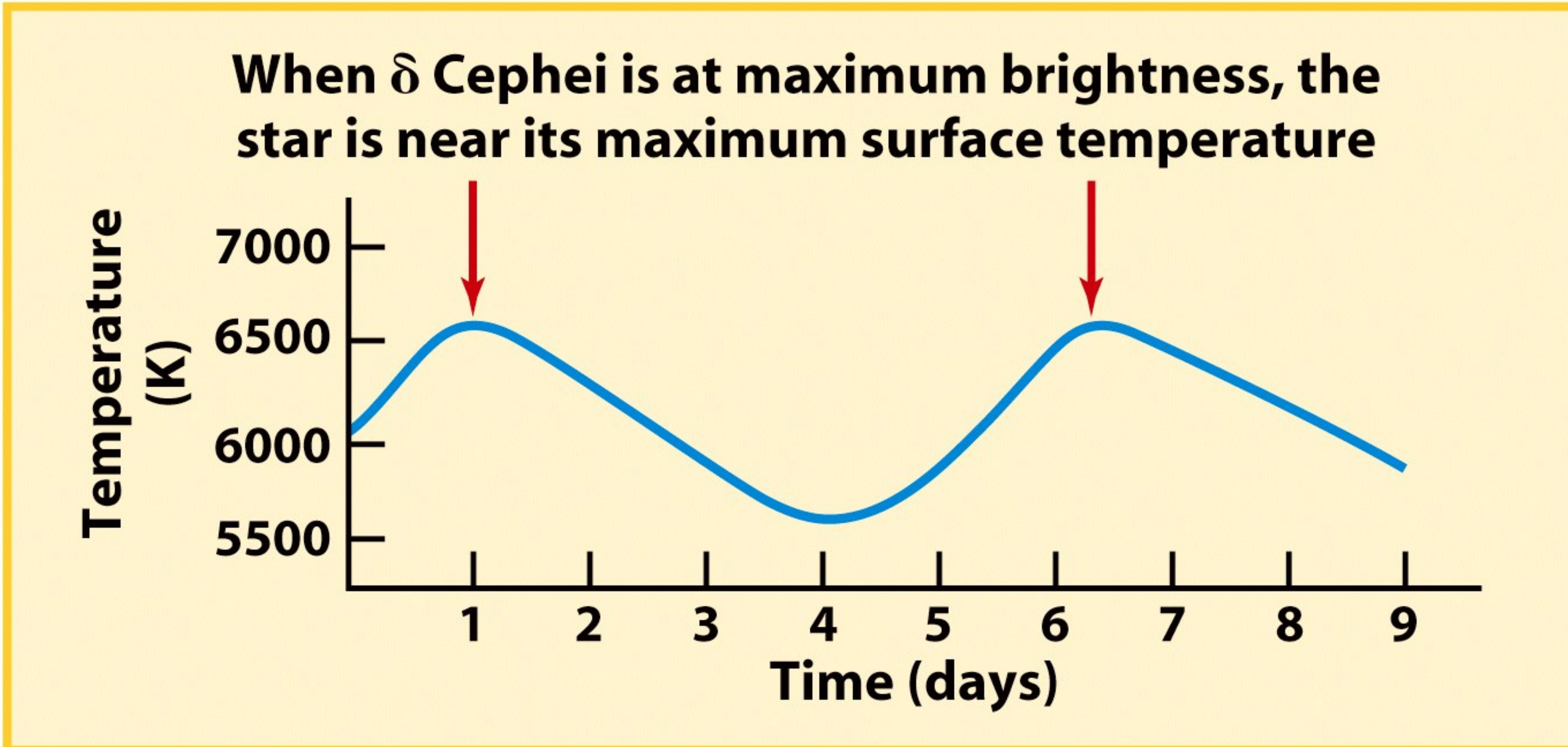
There is a direct relationship between Cepheid periods of pulsation and their luminosities



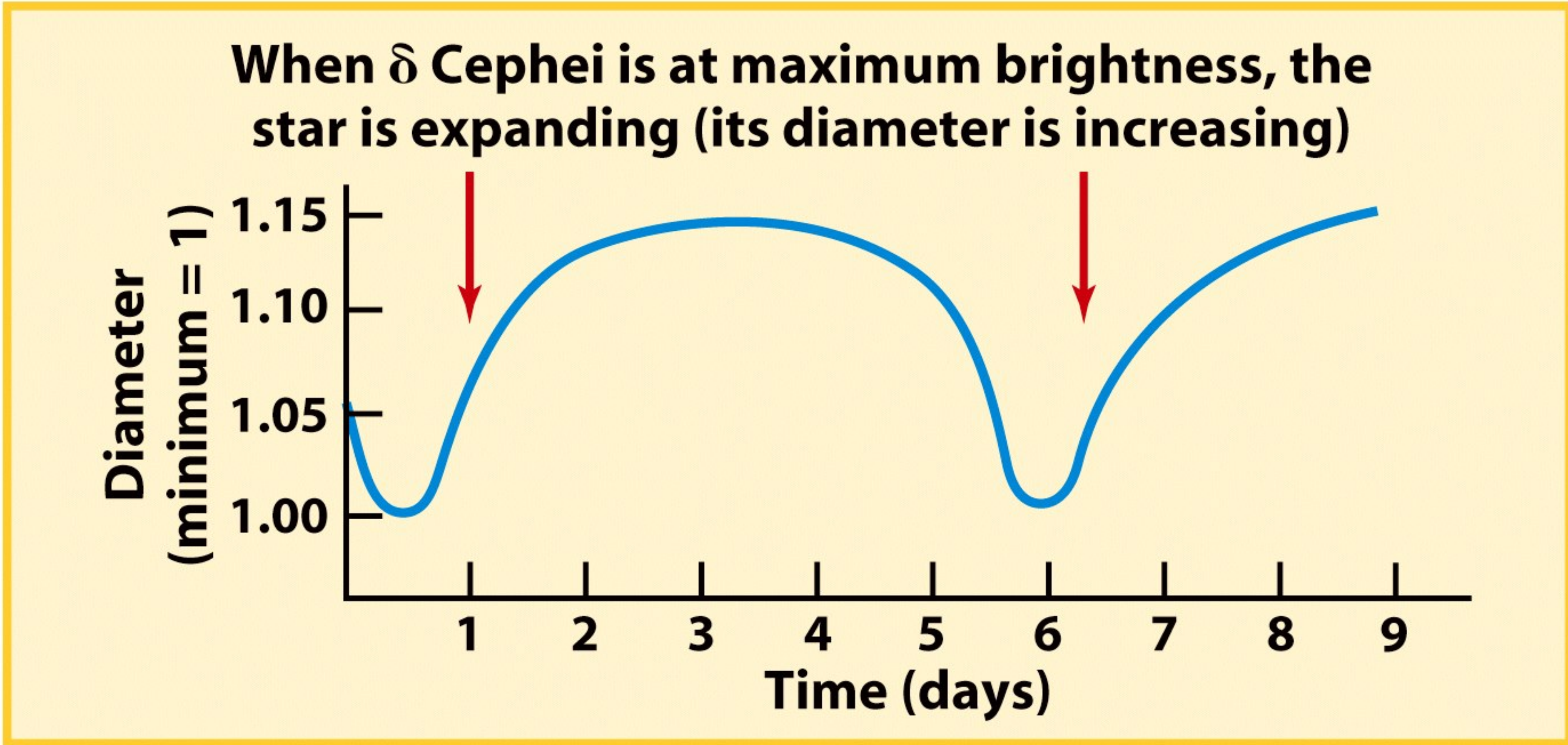
The light curve of δ Cephei (a graph of brightness versus time)



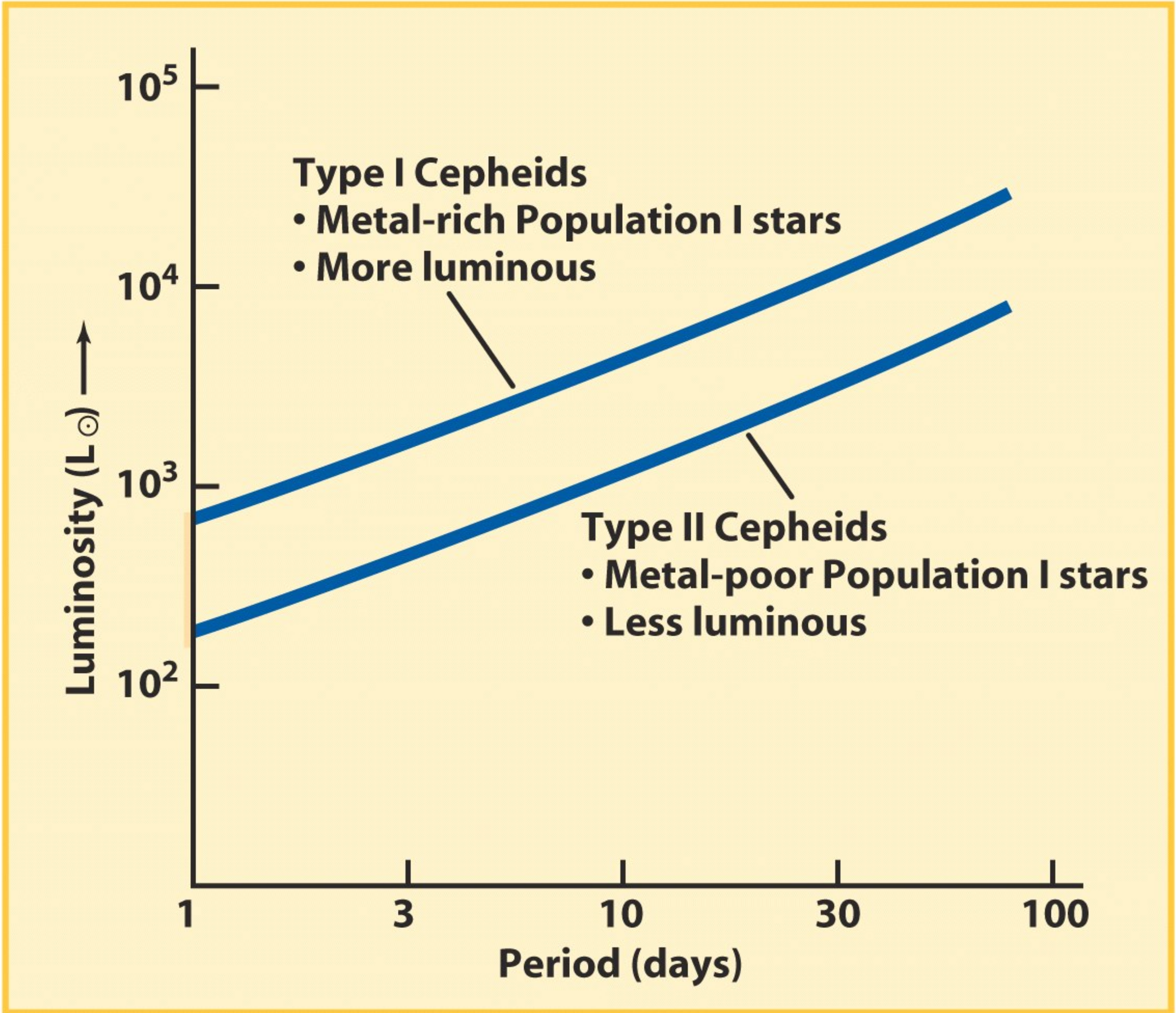
Radial velocity versus time for δ Cephei
(positive: star is contracting; negative: star is expanding)



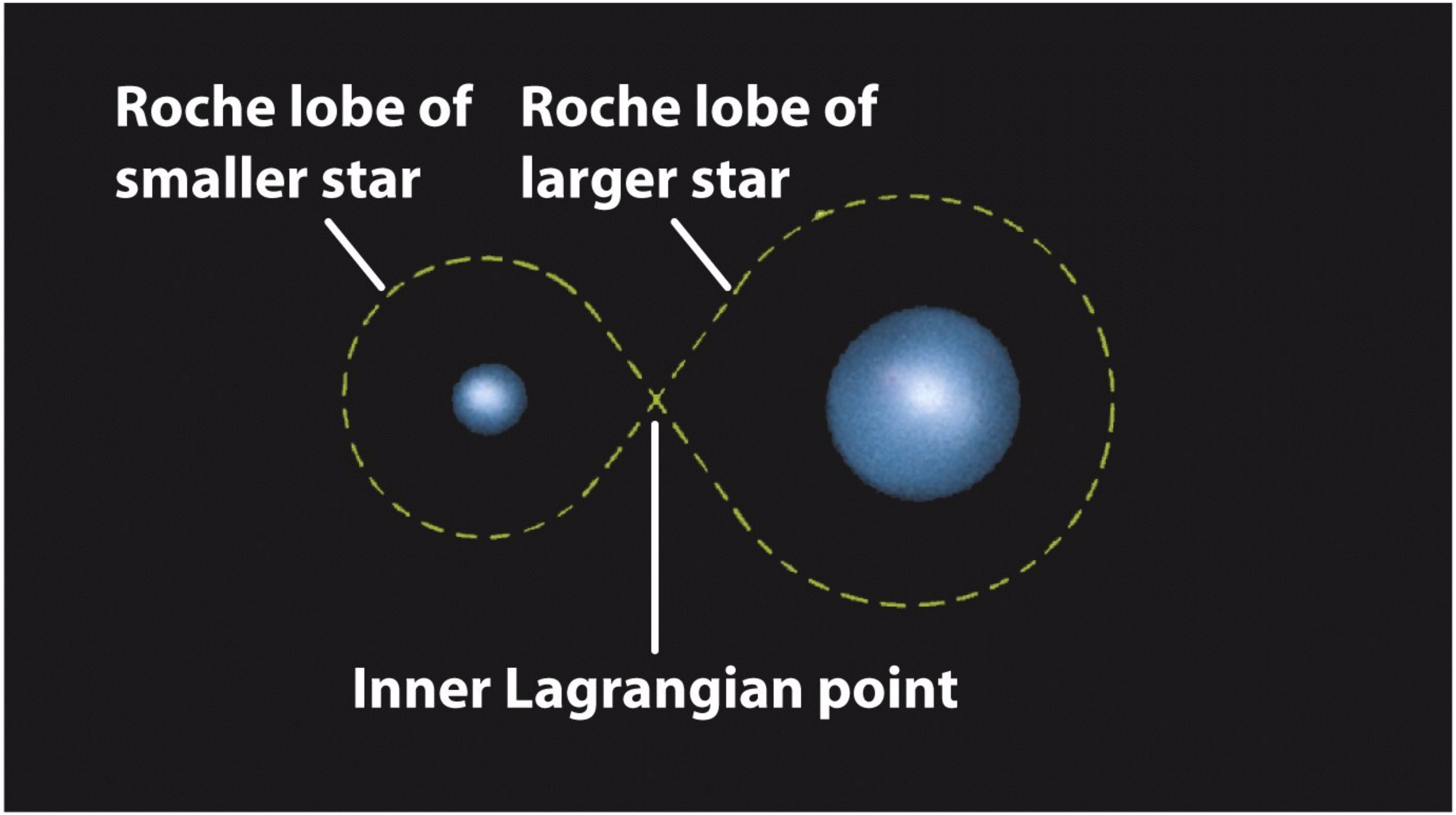
Surface temperature versus time for δ Cephei



Diameter versus time for δ Cephei


Type I Cepheids
• Metal-rich Population I stars
• More luminous
Type II Cepheids
• Metal-poor Population I stars
• Less luminous
Luminosity (L⊙)
10⁵
10⁴
10³
10²
1
3
10
30
100
Period (days)

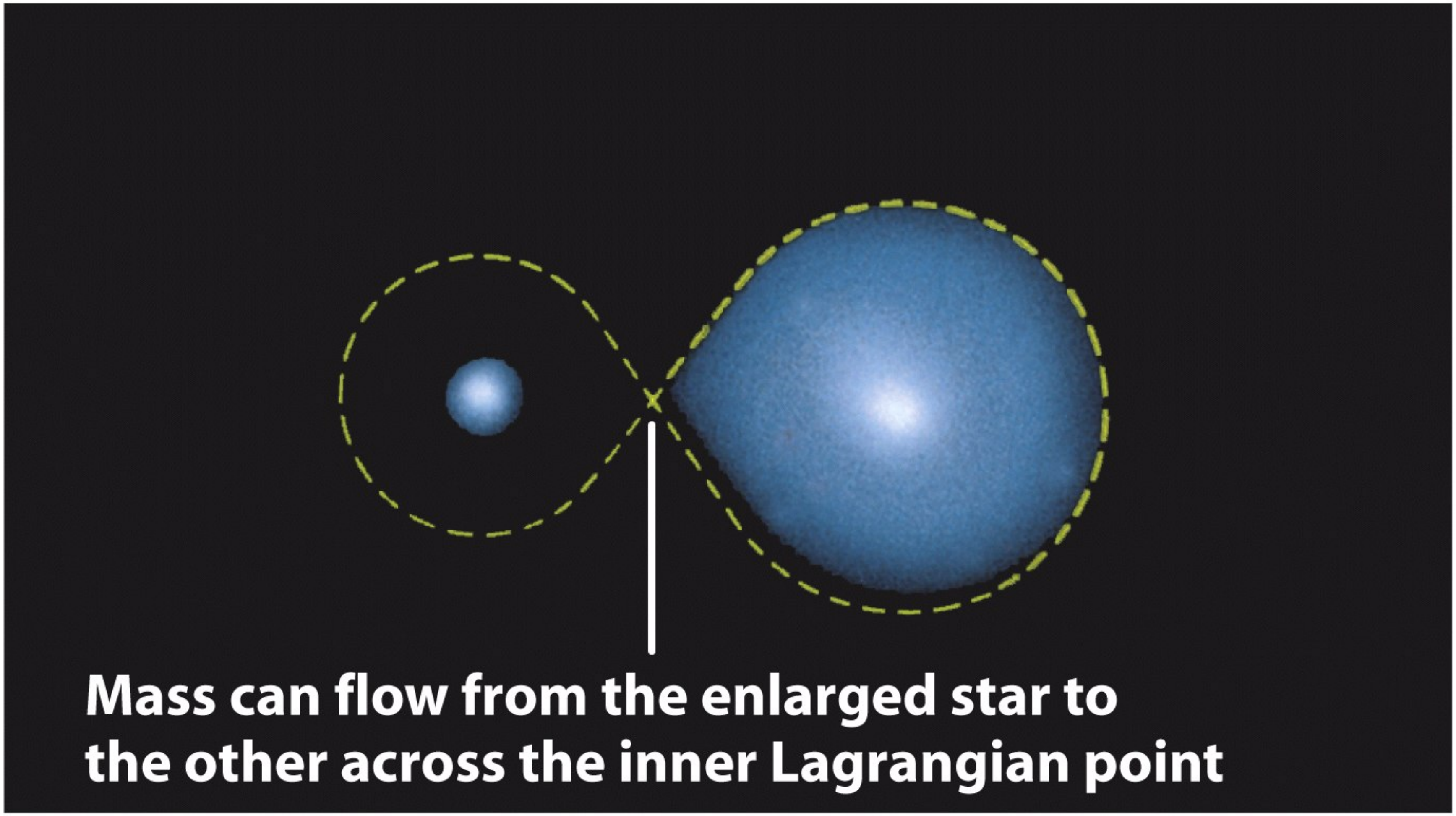
Mass transfer can affect the evolution of close binary star systems



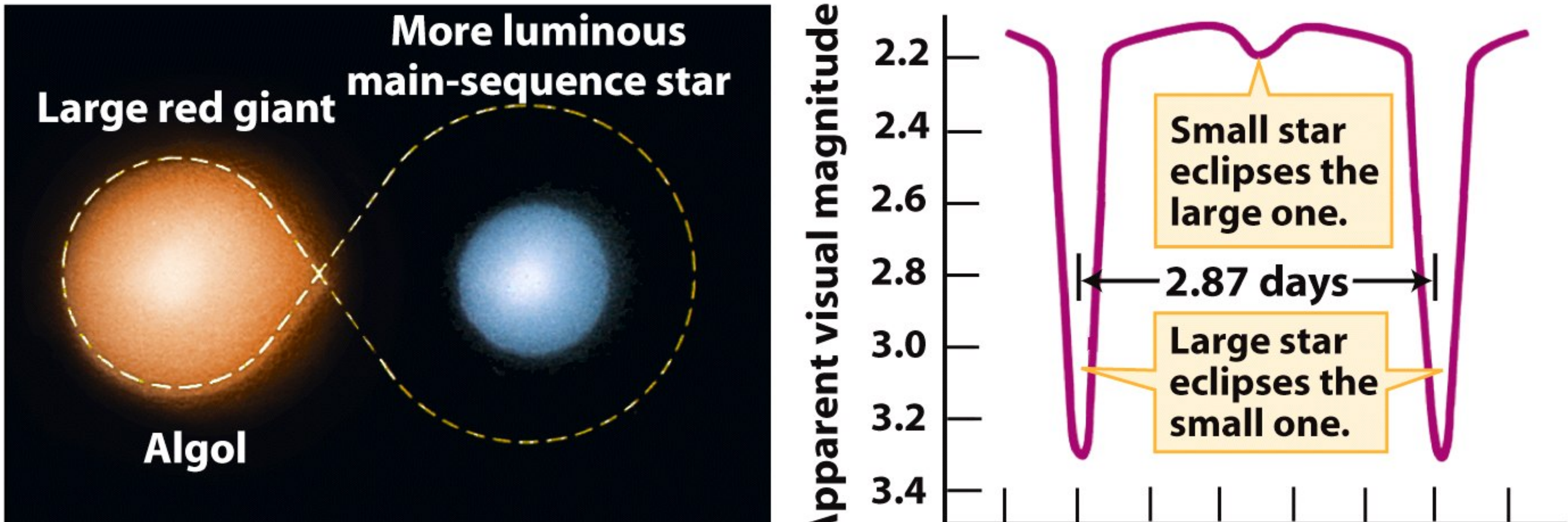
Detached binary: Neither star fills its Roche lobe.

Mass transfer in a close binary system occurs when one star in a close binary overflows its Roche lobe

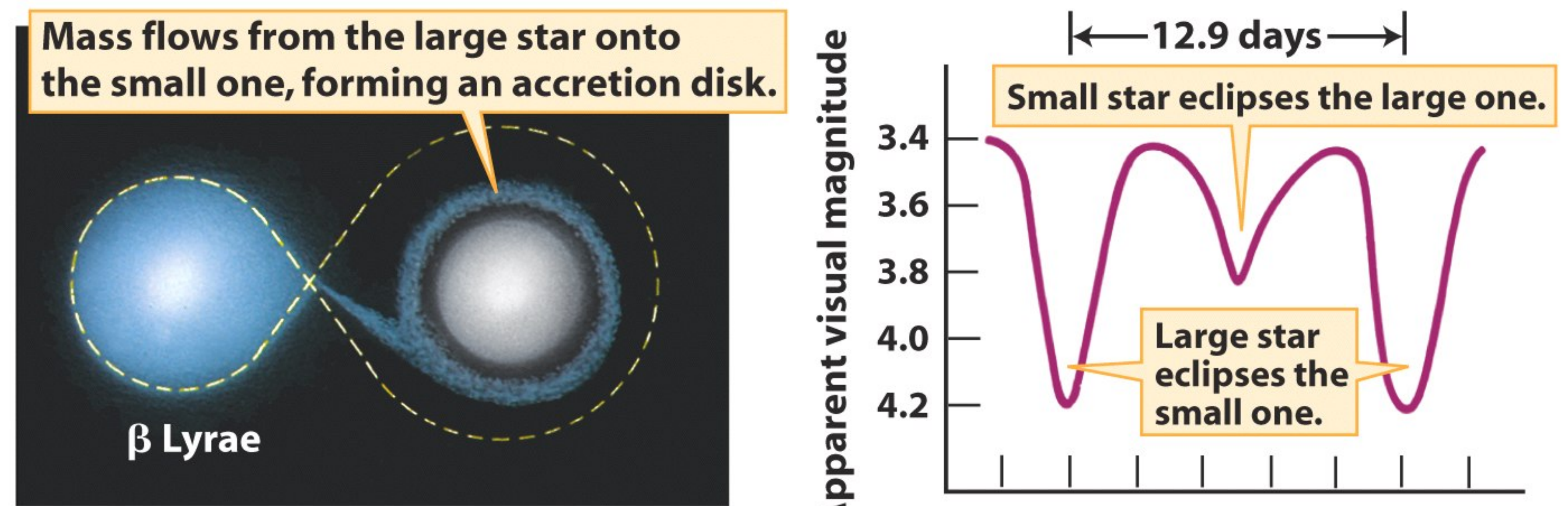
Gas flowing from one star to the other passes across the inner Lagrangian point



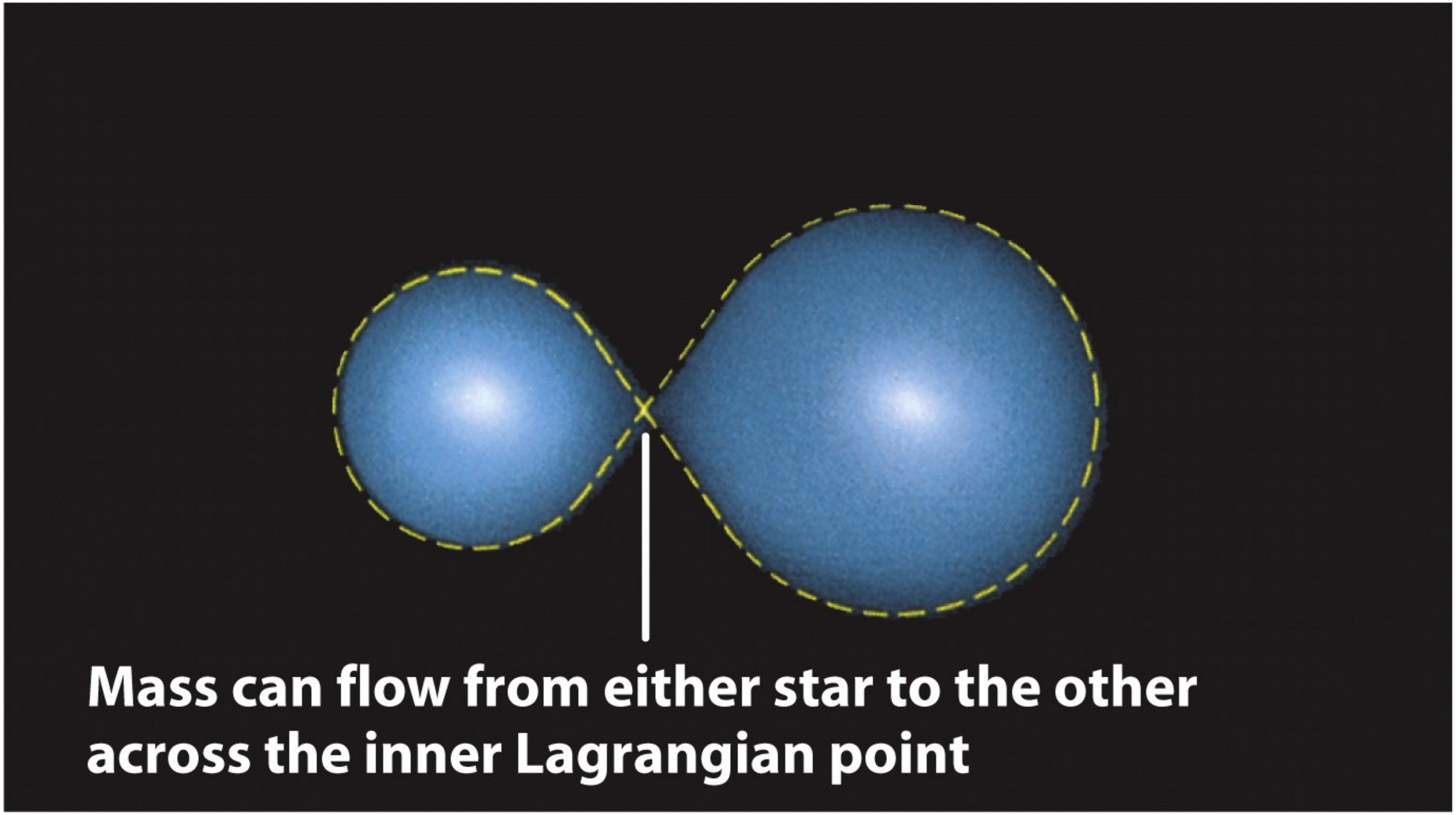
Semi-detached binary: One star fills its Roche lobe.



A semidetached binary

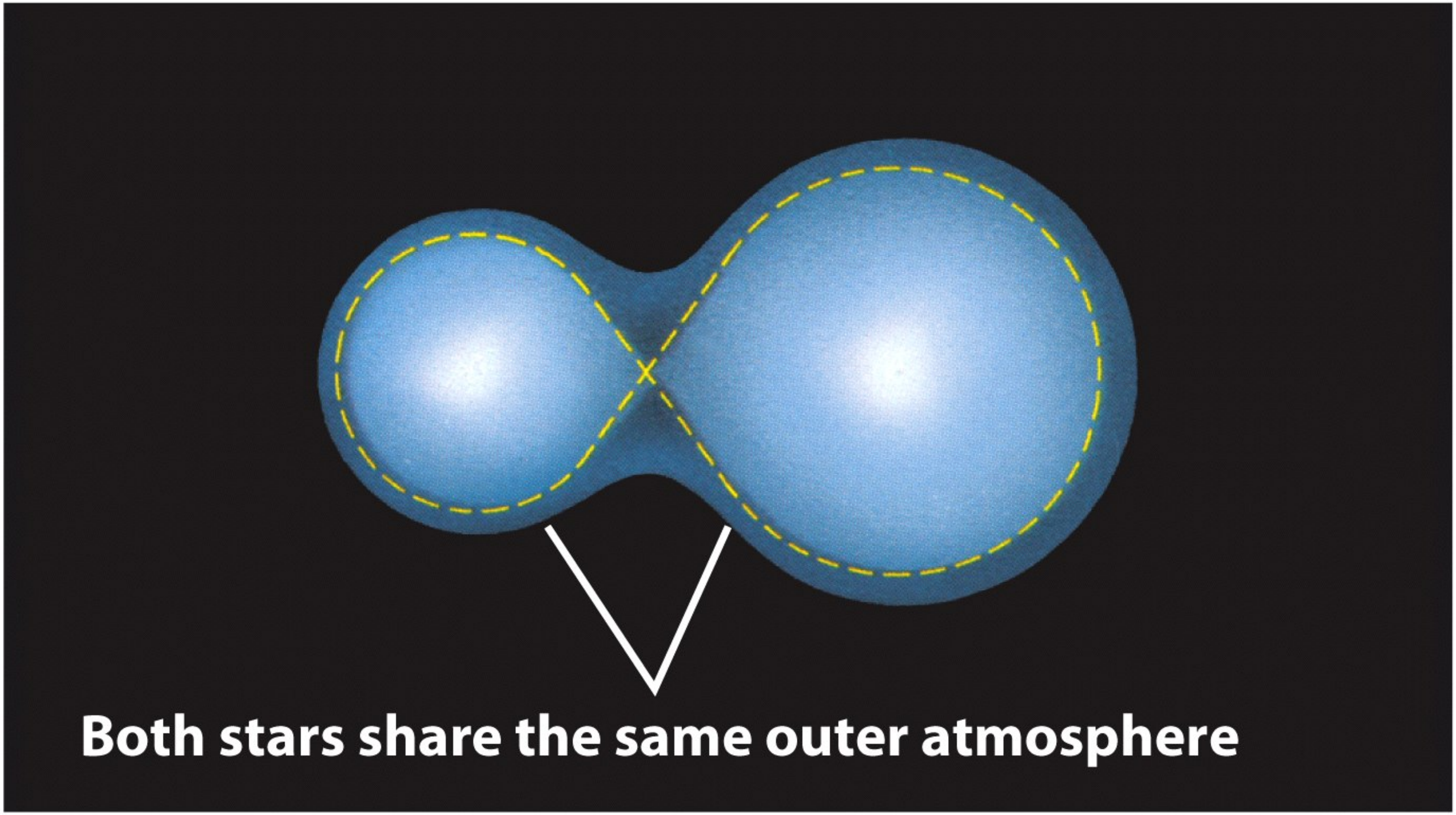


A semidetached binary with mass transfer

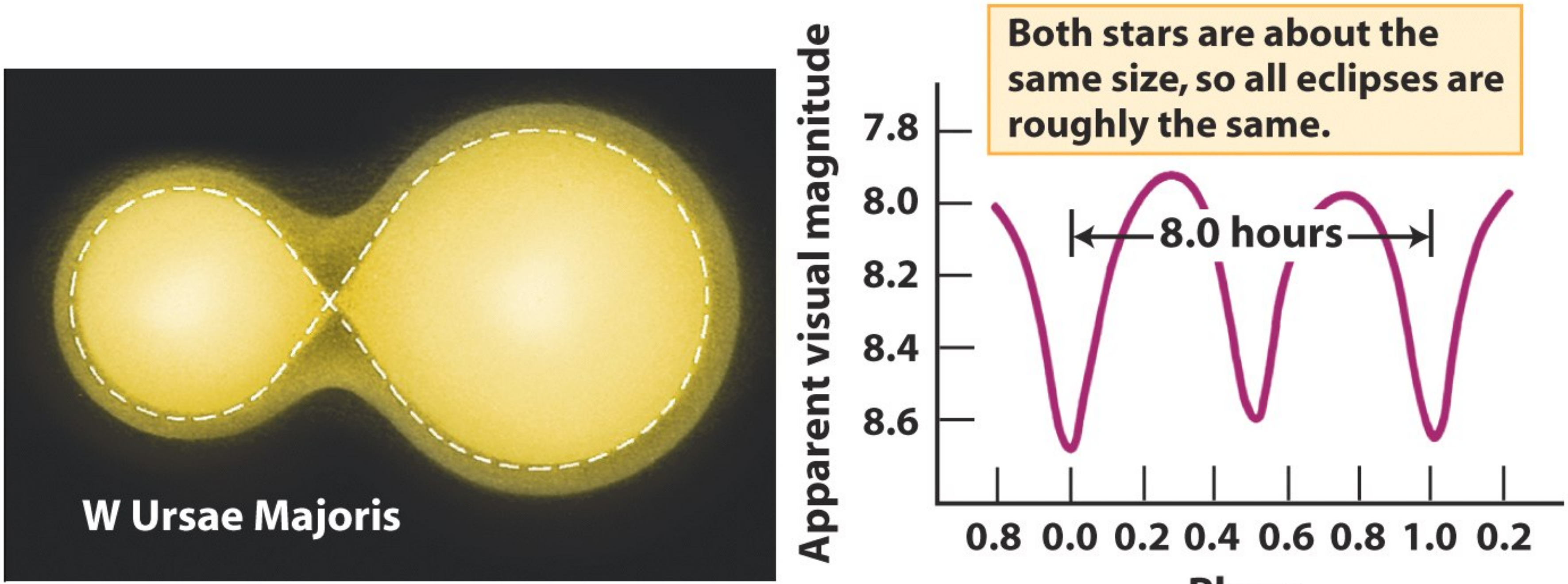


Contact binary: Both stars fill their Roche lobes.

This mass transfer can affect the developmental history of the stars that make up the binary system



Overcontact binary: Both stars overfill their Roche lobes.



An overcontact binary

Jargon I

- alpha particle
- Cepheid variable
- close binary
- color-magnitude diagram
- contact binary
- core helium fusion
- core hydrogen fusion
- degeneracy
- degenerate-electron pressure
- detached binary
- globular cluster
- helium flash
- helium fusion
- horizontal-branch star
- ideal gas
- inner Lagrangian point
- instability strip
- long-period variable
- main-sequence lifetime
- mass loss
- mass transfer
- metal-poor star
- metal-rich star
- overcontact binary
- Pauli exclusion principle
- period-luminosity relation
- Population I and Population II stars
- pulsating variable star
- red giant
- Roche lobe
- RR Lyrae variable
- semidetached binary
- shell hydrogen fusion
- triple alpha process
- turnoff point
- Type I and Type II Cepheids
- zero-age main sequence (ZAMS)
- zero-age main-sequence star

Jargon II

- accretion
- Barnard object
- bipolar outflow
- Bok globule
- circumstellar accretion disk
- cluster (of stars)
- cocoon nebula
- dark nebula
- dust grains
- emission nebula
- evolutionary track
- fluorescence
- giant molecular cloud
- H II region
- Herbig-Haro object
- interstellar extinction
- interstellar medium
- interstellar reddening
- nebula (*plural* nebulae)
- nebulosity
- OB association
- open cluster
- protoplanetary disk (proplyd)
- protostar
- recombination
- reflection nebula
- stationary absorption lines
- stellar association
- stellar evolution
- supernova remnant
- supersonic
- T Tauri star